Characterisation of respirable indoor particulate matter in South African low-income settlements

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by

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Doctor of Philosophy in Geography and Environmental Management

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ABSTRACT

Air pollution is a leading health risks that individuals face daily. Emissions and contribution from scheduled industrial sources has been a focus within South Africa air quality management for decades. In recent years, the importance of dense, low-income residential environments has been recognised due to ambient air quality measurements conducted with these communities. Extremely high levels of particulate matter were recorded in part created by residential solid fuel combustion.

Indoor air quality studies in South Africa tend to have a narrow geographic focus while investigating small sample groups, mostly on a case-study basis. Existing studies further have not considered the apportionment of indoor sources. These limitations have impeded a comprehensive understanding of the air pollution problem facing our most vulnerable population groups.

In this thesis, the respirable (PM_4) fraction of indoor particulate matter was examined within two coal-burning- (KwaDela and KwaZamokuhle), one urban- (Jouberton), and two wood-burning- (Agincourt and Giyani) low-income settlements in South Africa. This included: i) a field evaluation of the photometric particulate monitoring used; ii) an assessment of the status of air quality with respect to the PM_4 mass concentrations; iii) the identification of possible sources contributing to the indoor environment; and iv) an

evaluation of the relationship between the observed synoptic circulations, local meteorology and indoor PM_4 loadings.

PM_4 data were collected in the indoor environment of households within the above mentioned settlements, between 2013 and 2017, across 21 individual seasonal sampling campaigns. Three main method of sampling were conducted, namely i) continuous monitoring by photometric instruments (DustTrak, DustTrak II, and SidePak); ii) gravimetric filter sampling which were analysed by WD-XRF for the elemental chemical composition; and iii) a collocated sampling method for the field evaluation of the instrumentations.

The photometric instruments both over-and underestimated the continuous indoor PM_4 mass concentrations which resulted in the development of twenty-nine (29) PCFs. The comparability of different instrument models improved between 15 and 46% when applying instrument-specific PCFs calculated for the specific micro-environment. A conversion factor of 0.92 was determined to convert indoor PM_4- to $PM_{2.5}$ mass concentration. This enables some comparison of the measurements with ambient air quality standards.

The low-income settlement had a mean (±SD) indoor PM_4 loading of 116 (±357) $\mu g.m^{-3}$. Coal-burning (137 (±403) $\mu g.m^{-3}$) communities experiencing PM_4 loadings which are three times higher than the urbanised- (53 (±171) $\mu g.m^{-3}$) and wood-burning (58 (±143) $\mu g.m^{-3}$) communities. A distinct bi-modal diurnal pattern is present within all the communities. The indoor $PM_{2.5}$ were above the 24-hr NAAQS (40 $\mu g.m^{-3}$) and WHO (25 $\mu g.m^{-3}$) guideline for~57 and 76% of the daily averages. The qualitative source contribution was estimated based on the elemental mass concentrations, crustal enrichment factors, and principal component analysis (PCA). The main sources included crustal soil-, road traffic-, solid fuel combustion-, waste burning-, and biomass burning emissions.

All households (regardless of their fuel use) in dense-, low-income settlements experience high levels of indoor PM_4. Current health impact assessments likely grossly underestimate the scale of the problem. This highlights the need to improve understanding at a local scale and formulate mitigation strategies for all low-income communities individually.

Key terms: indoor air quality, low-income settlements, residential solid fuel combustion, respirable particulate matter, source apportionment, South Africa,

In loving memory of my mother,

Hulda Elizabeth Language (1966-2008),

who always inspired me to be committed to everything I pursue.

To my grandparents:

William Robert Language (1936-2019)
&
Magrietha Susanna Language (1938-2010)

Casper Nicolaas Bezuidenhout (1942-2008)
&
Anna Magrietha Steenkamp (1942-2012)

PREFACE

This thesis is submitted for the degree of Doctor of Philosophy (PhD) in Geography and Environmental Management at North-West University (NWU). The research described herein was conducted under the supervision of Prof Stuart J. Piketh and Prof Roelof P. Burger in the Unit for Environmental Science and Management, NWU, between July 2013 and December 2017.

I was personally involved in the collection of data, analysis of collected data, as well as the writing of manuscripts and this thesis document. I declare that this thesis is my own unaided work and that all references to, or quotations from, the work of others are fully and correctly cited. This work, to the best of my knowledge, has not been submitted for any degree at any other university.

Air pollution is one of the main health risk problems facing civilisation today. It is thought of as having no confining boundaries and thus impacts on both developed and developing countries without precedence *(World Health Organization, 2000)*. The Constitution of the Republic of South Africa makes provisions for the protection of the environment for current and future generations. It states that everyone has the right to live in an environment that does not negatively impact on their health or welfare *(South Africa, 1996)*, this includes having access to clean air. There is a disparity in the knowledge surrounding ambient- and indoor air quality in South Africa. Ambient air quality is fairly well understood in South Africa, however, there is very little information on indoor air quality. Thus, the aim of this research project is to evaluate the state of respirable particulate matter (PM_4) within the indoor environment of low-income residential settlements in South Africa across various spatial and temporal resolutions. In particular, the objectives of this study are to:

(i) evaluate the use of photometric particulate monitors ;
(ii) assess the status of indoor air quality with respect to the mass concentration of PM_4;
(iii) characterise sources associated with the indoor PM_4 trace elements; and
(iv) investigate the influence of synoptics on local meteorology and its associated impact on the mass concentrations of indoor PM_4 measured in the indoor environment.

The study will contribute to understanding the current state of PM_4 pollution within South Africa. It will also provide input into further possible health-related studies and inform the development of indoor particulate matter guidelines and standards.

The data used, to achieve the above mentioned aims and objective, were obtained from several ethically approved research projects, conducted by the NWU Climatology Research Group (C.R.G) in collaboration

with the NOVA Institute (NOVA), The South African Medical Research Council (SA-MRC), and the National Institute for Communicable Diseases (NICD) . The projects included:

- ***The Quality of Life Baseline Survey in Selected Communities Surrounding Sasol-Secunda*** (Sasol Offset Pilot Study) project funded by SASOL Synfuels. The project was supported by the NOVA and NWU. Research ethics clearance was obtained from the NWU's Health Research Ethics Committee (HREC) (certificate NWU-00066-13-A3).
- ***The Execution of a Household Emissions Offset Study in the Highveld Priority Area*** (Eskom Offset Pilot Study) funded by ESKOM Holdings SOC Limited. The project was supported by the NWU, NOVA, Council for Scientific and Industrial Research (CSIR), and Prime Africa Consultants. Ethics clearance for the research was granted by the NWU's HREC (certificate NWU-0158-14-S3).
- ***The Prospective Household observational cohort study of Influenza, Respiratory Syncytial virus and other respiratory pathogens community burden and Transmission dynamics in South Africa Study*** (PHIRST) supported by the cooperative agreement between the United States Centre for Disease Control and Prevention (CDC) and the South Africa National Health Laboratory Services (SA-NHLS) including the NICD. Ethical approval for the study was obtained from the University of the Witwatersrand, Johannesburg HREC (certificate 150808) – *Figure A.1*.
- ***The infection Diseases Early-Warning System*** (iDEWS) project supported by Science and Technology Research Partnership for Sustainable Development Programme of Japan International Cooperation Agency/Japan Agency for Medical Research and Development and the Applied Centre for Climate and Earth Systems Science program of National Research Foundation and Department of Science and Technology in South Africa. Research ethics clearance was granted by the South African Medical Research Council Research Ethics Committee (certificate EC005-3/2014) – *Figure A.2*.

This thesis comprises of seven chapters. ***Chapter 1 – Overview*** provides the background and justification for the study, including a detailed literature review exploring the state and knowledge surrounding indoor air quality. The research aim, objectives, and study design are also presented. ***Chapter 2 – Data acquisition and analysis methodology*** contains a detailed description of the sampling procedures, sample analyses techniques and analytical procedures implemented for data interpretation. Furthermore, the ethical considerations, assumptions and limitations surrounding the study are elaborated upon. ***Chapter 3 – Field evaluation of photometric instruments*** evaluates the use of photometric instrumentation within the indoor environment of residential homes by investigating the variations in calibration factors within the microenvironment, inter-comparing instruments fitted with the same respirable particulate inlet as well as instruments fitted with inlets of varying size fractions. ***Chapter 4 – Characterisation and source***

identification of respirable indoor particulate matter focusing on characterising particulate mass concentration and associated trace elements within the indoor environment of residential households as well as identifying possible sources contributing to particulate aerosols. ***Chapter 5 – Weather of the study area*** presents the synoptic- and local meteorological conditions for each measurement campaign, conducted during the study period. . ***Chapter 6 – Summary and conclusions*** provides a synopsis of the main findings associated with each objective and presents the conclusions to the study as a whole.

Segments of the thesis have been published in the *Clean Air Journal*, *WIT Transactions on Ecology and The Environment* and in *Atmosphere*. The publications include:

- Wernecke, B., **Language, B.**, Piketh, S., Burger, R.P. 2015. Indoor and outdoor particulate matter concentration on the Mpumalanga Highveld – A case study. Clean Air Journal, 25 (2), p12.
- **Language, B.**, Piketh, S., Burger, R.P. 2016. Correcting respirable photometric particulate measurements using a gravimetric sampling method. Clean Air Journal, 26 (1), p10.
- **Language, B.**, Piketh, S., Wernecke, B., Burger, R.P. 2016. Household air pollution in South African low-income settlements: a case study. WIT Transactions on Ecology and The Environment, 207, p227.
- Kapwata, T., **Language, B.**, Piketh, S.J., Wright, C.Y. 2018. Variation of Indoor Particulate Matter Concentrations and Association with Indoor/Outdoor Temperature: A Case Study in Rural Limpopo, South Africa. Atmosphere, 9, 124.
- Adesina, J.A., Piketh, S.J., Qhekwana, M., Burger, R.P., **Language, B.**, Mkhatshwa, G. 2020. Contrasting indoor and ambient particulate matter concentrations and thermal comfort in coal and non-coal burning households at South Africa Highveld. Science of The Total Environment, 699, p134403.

Sections of the work have also been presented at both local and international peer-reviewed conferences. Internationally the work was presented at the *Air Pollution Conference*; at the *Indoor Air Conference*; the *Joint IAPSO-IAMAS-IAGA Assembly*; and at the *Joint 14th iCACGP Quadrennial Symposium/15th IGAC Science Conference*. The aforementioned comprised the following:

- **Language, B.**, Burger, R.P. and Piketh, S.J. 2016. Household air pollution in South African low-income settlements: A Case Study *(Presentation – Air Pollution Conference, Crete, Greece)*
- **Language, B.**, Burger, R.P. and Piketh, S.J. 2016. Indoor Air Quality in South Africa: A case study in a small, isolated low-income settlement. *(Poster – Indoor Air Conference, Ghent, Belgium)*

- **Language, B.**, Burger, R.P. and Piketh, S.J. 2017. Quantifying source contribution to indoor particulate matter in low-income settlements in South Africa. *(Presentation – Joint IAPSO-IAMAS_IAGA Assembly, Cape Town, South Africa)*
- Piketh, S.J., Burger, R.P., Walton, N., **Language B**. and Formenti, P. 2017. Source apportionment of air pollutants at multiple Highveld Townships in South Africa – Implications for air quality management and human health. *(Presentation - Joint IAPSO-IAMAS-IAGA Assembly, Cape Town, South Africa)*
- **Language, B.**, Cohen, C., Kahn, K., Martinson, N., Mathee, A., McMorrow, M., Tempia, S. and Piketh, S.J. 2018. Respirable particulate matter within residential homes in two South African communities, 2016-2017. *(Poster - Indoor Air Conference, Philadelphia, United States of America)*
- **Language, B.**, Wright, C.Y., Burger, R.P. and Piketh, S.J. 2018. Indoor particulate matter, trace elements, and temperature variations: a case study in rural Giyani, Limpopo, South Africa. *(Poster – Joint 14th iCACGP Quadrennial Symposium/15th IGAC Science Conference, Takamatsu, Japan)*
- Burger, R.P., **Language, B.**, Lindeque, F., Nkosi, N., Muyemeki, L. and Piketh, S.J. 2018. Challenging the future of air pollution in South Africa. *(Presentation – Joint 14th iCACGP Quadrennial Symposium/15th IGAC Science Conference, Takamatsu, Japan)*

Locally work was presented at the *National Association for Clean Air Conference (NACA)*, *National Laboratory Association Test and Measurement Conference*, and at the *Young Spectroscopist's Symposium*. The above-mentioned included the following:

- **Language, B.**, Burger, R.P. and Piketh, S.J. 2015. Comparison of respirable particulate measurements from direct-reading photometric instruments and a gravimetric sampling method. *(Presentation – National Laboratory Association - Test and Measurement Conference, Somerset West, South Africa)*
- Wernecke, B., **Language, B.**, Piketh, S.J, Burger, R.P. 2015. Indoor and outdoor particulate matter concentration on the Mpumalanga Highveld – A case study. *(Presentation – NACA Conference, Bloemfontein, South Africa)*
- **Language, B.**, Piketh, S.J., and Burger, R.P. 2015. Correcting respirable photometric particulate measurements using a gravimetric sampling method. *(Presentation – NACA Conference, Bloemfontein, South Africa)*
- Oosthuizen, R., Garland, R.M., John, J., Piketh, S.J., **Language, B.,** and Mkhatshwa, G. 2016. Human Health Risk Assessment from ambient and indoor air pollution in an area where coal is used as an energy carrier. *(Presentation - NACA Conference, Nelspruit, South Africa)*

- **Language, B.** 2016. Aerosol filter analysis using WD-XRF. *(Presentation – Young Spectrometrist Society Symposium, Pretoria, South Africa)*
- **Language, B.**, Qhekwana, M.M., Letsholo, T.A., Burger, R.P. and Piketh, S.J. 2018. The application of photometric instruments to air quality monitoring in South Africa: an indoor case study in residential settlements. *(Poster - NACA Conference, Vanderbijlpark, South Africa)*

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Fieldworkers from the NOVA Institute, South African Medical Research Council, and the National Institute for Communicable Diseases are thanked for their assistance during fieldwork campaigns. I gratefully acknowledge the local authorities for permitting us to work in the various communities and especially the occupants of the households for allowing the installation of measuring equipment in their homes. I am very thankful for the warm welcome each household has given us as well as their time and cooperation.

I am privileged to have been supervised by, Prof Stuart J. Piketh and Prof Roelof P. Burger, throughout this postgraduate research process. Without their assistance and dedicated involvement, this PhD thesis would have never been realised. I thank them for providing a stimulating and productive environment within their research unit and would like to express my sincerest gratitude to my supervisors for being incredible mentors. They also provided the funding and opportunities for me to not only complete my research but also to actively participate and share my work at both national and international conferences. My PhD journey has been an incredible experience and I thank them for their scientific guidance, enthusiasm, constructive criticism, and instilling in me a desire to never stop learning and improving my knowledge.

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LIST OF EQUATIONS

ABBREVIATIONS

µm	-	Micrometre
µg.m-3	-	Micrograms Per Cubic Metre
AEL	-	Atmospheric Emissions Licenses
AHI	-	Annual Household Income
ALRI	-	Acute Lower Respiratory Infection
AMS	-	Ambient Monitoring Station
APPA	-	Atmospheric Pollution Prevention Act
AQG	-	Air Quality Guidelines
AQI	-	Air Quality Index
AQMP	-	Air Quality Management Plans
BGM	-	Borosilicate Glass Microfiber
C.R.G.	-	Climatology Research Group
CDC	-	United States Centre for Disease Control and Prevention
CMB	-	Chemical Mass Balance
CRA	-	Comparative Risk Assessment
CSIR	-	Scientific and Industrial Research
CSPSS	-	China Source Profile Shared Services
DEA	-	Department of Environmental Affairs
DT	-	DustTrak Model 8520
DTII	-	DustTrak II Model 8530
EA	-	Enumeration Area
EF	-	Enrichment Factor
EHP	-	Environmental Protection Agencies
EPA	-	Environmental Protection Agency
ETS	-	Environmental Tobacco Smoke
FA	-	Factor Analysis
g	-	Grams
HAP	-	Household Air Pollution
HDSS	-	Health and Socio-Demographics Surveillance System
HPA	-	Highveld Priority Area
HRA	-	Health Risk Assessment
HREC	-	Human Research Ethics Committee
IAQG	-	Indoor Air Quality Guidelines
iDEWS	-	The infectious Disease Early-Warning System

IPWM	-	Integrated Pollution and Waste Management
IQR	-	Inter Quartile Range
ISFB	-	Indoor Solid Fuel Burning
ITCZ	-	Inter-Tropical Convergence Zone
$L.min^{-1}$	-	Litres Per Minute
LOD	-	Limit Of Detection Limit
LOQ	-	Limit Of Quantification
m.a.m.s.l.	-	meters above mean sea level
MCE	-	Mixed Cellulose Ester
MRA	-	Multiple Regression Analysis
N	-	Number of Samples
NAAQS	-	National Ambient Air Quality Standards
NDoH	-	National Department of Health
NEMA	-	National Environmental Management Act
NEMAAQA	-	Air Quality Offset
NEMAQA	-	National Environmental Management Air Quality Act
NGOs	-	Non-Governmental Organisations
NICD	-	National Institute for Communicable Diseases
NIOSH	-	National Institute for Occupational Safety and Health
NIST	-	National Institute of Standards and Technology
NOVA	-	NOVA Institute
NSFB	-	Non-Solid Fuel Burning
NWU	-	North-West University
OSFB	-	Outdoor Solid Fuel Burning
OSHA	-	Occupational Safety and Health Administration
PCA	-	Principal Component Analysis
PCF	-	Photometric Calibration Factor
PhD	-	Doctor of Philosophy
PHIRST	-	The Prospective Household observational cohort study of Influenza, Respiratory Syncytial virus and other respiratory pathogens community burden and Transmission dynamics in South Africa Study
PM	-	Particulate Matter
PM_1	-	Particulate Matter with an aerodynamic diameter ≤ 1 micrometre
$PM_{2.5}$	-	Particulate Matter with an aerodynamic diameter ≤ 2.5 micrometre
PM_4	-	Respirable Particulate Matter with an aerodynamic diameter ≤ 4 micrometre
PM_{10}	-	Particulate Matter with an aerodynamic diameter ≤ 10 micrometre

PMF	-	Positive Matric Factorisation
RDP	-	Reconstruction and Development Programme
SA-MRC	-	South African Medical Research Council
SA-NHLS	-	South Africa National Health Laboratory Services
SAWS	-	South African Weather Service
SD	-	Standard Deviation
SP	-	SidePak AM510
SSA	-	Statistics South Africa
TB	-	Tuberculosis
TSP	-	Total Suspended Particles
VTAPA	-	Vaal Triangle Air Shed Priority Area
WBPA	-	Waterberg-Bonjala Priority Area
WD-XRD	-	Wavelength-Dispersive X-Ray Fluorescence
WHO	-	World Health Organisation

CHAPTER 1: OVERVIEW

This chapter provides the background and justification for the study, including a detailed literature review exploring the state of knowledge surrounding indoor air quality. A particular focus has been placed on particulate aerosols, indoor air quality, health impacts of airborne particulate matter, and air quality management guidelines and legislation. Lastly, the research aim, objectives, and study design are outlined.

****

1.1. Introduction

There has been a sharp increase in the global population since the early 1800s. The population was ~7.6 billion in 2017 and is projected to grow to approximately 9 billion by 2050 *(United Nations, 2017)*. In 1950, a mere 30% of the global population resided in urban environments. This has increased to 55% in 2018 and is projected to rise to 68% by 2050 *(United Nations, 2018)*. The growing population results in the expansion of anthropogenic activities *(Steffen et al., 2011)*. The impact of these anthropogenic activities on the environment has intensified so much that in many ways it has surpassed the impacts associated with natural processes *(Crutzen, 2006)*. Due to the sheer scale of the changes associated with anthropogenic activities the global change research community has recognised the current geological epoch as the Anthropocene *(Crutzen, 2002; Steffen et al., 2011)*. The epoch has a number of biotic and geochemical markers, which includes climate change, ocean acidification, ozone depletion, atmospheric aerosol loading, the phosphorus and nitrogen cycles, global freshwater use, land system changes, the loss of biodiversity, and chemical pollution *(Gillings & Hagan-Lawson, 2014; Steffen et al., 2015)*. Changes impacting negatively on the above-mentioned markers result in increased levels of environmental pollution along various pathways such as air, water, and soil *(Olawoyin, 2018)*.

Since the turn of the twentieth century there have been a number of significant air pollution events such as the Meuse Valley fog of Belgium in December 1930 *(Firket, 1936; Nemery et al., 2001)*, the Los Angles photochemical smog of the 1940s *(Cadle & Wohlers, 1952; Magill, 1949)*, Donora smog in Pennsylvania in October 1948 *(Schrenk et al., 1949; Snyder, 1994)*, London's Great Smog in December 1952 *(Davis & Bell, 2002; Scorer, 1954)*, and more recently the Bhopal chemical factory accident in India in 1984 *(Narayan, 1990; Tachakra, 1989)*. Historical happenings such as these have had considerable impacts on human and environmental health and thus encouraged researchers and legislators alike to invest time into studying the problem and finding means of managing air pollution as it is one of the main environmental

health problems facing civilisation today. It is thought of as having no confining boundaries and thus impacts on both developed and developing countries without precedence *(Akimoto, 2003; Lelieveld, 2017)*.

Air pollutants are brought about by various anthropogenic activities which can be categorised as rural- (mining and agriculture), industrial- (power generation, metal industries, and chemical manufacturing), mobile- (combustion-engine vehicles, aircraft, and fugitive dust from vehicular traffic), community- (municipal waste dumping and incineration, space heating, and cooking), and indoor sources (tobacco smoke, combustion for cooking and heating, and emission from materials). In addition, there are also a number of natural sources, both physical and biological, contributing to air pollution *(World Health Organization, 2000)*. The air pollutants resulting from any of these activities can contribute to exposure in both the ambient and indoor environments.

The Global Burden of Disease Study ranked ambient particulate pollution as the 9th and household air pollution (HAP) as the 3rd most influential risk factor attributing to the disease burden. However, for southern sub-Saharan Africa these factors are ranked 25th and 7th, respectively *(Lim et al., 2012)*. Nearly 2.8 billion people (41% of the 2010 global population, 95%CI: 37-44) rely on solid fuels as their primary energy source for cooking. In sub-Saharan Africa the use of solid fuels is even more prevalent (77%, 95% CI: 74, 57). Regions within Southeast Asia, Western Pacific, Eastern Mediterranean, Americas, and Europe showed a steady decline (between 25 and 36%) of household solid fuel combustion between 1980 and 2010. Africa had a mere 10% decline during the same period. The number of people exposed to solid fuel emission has, however, stayed stable due to the growing population (Bonjour *et al.*, 2013). In 2010, cooking with residential solid fuels accounted for 37% (2.8 of 6.9 $\mu g.m^{-3}$) of ambient $PM_{2.5}$ in southern Sub-Saharan Africa *(Chafe et al., 2014)*. These estimations of solid fuel use do not account for fuels used for heating activities, thus these numbers are likely to be higher.

The energy ladder model, without reservation, assumes that consumers on a residential scale will make use of the most efficient fuel they can afford. Thus, it suggests that solid fuels such as crop residues, wood, charcoal, and coal are mostly used by the impoverished, however, in some cases, solid fuels are preferred for personal reasons including tradition *(Hiemstra-van der Horst & Hovorka, 2008; van der Kroon et al., 2013)*. Household will often use multiple type of fuel to satisfy their energy needs. This behaviour is known as fuel stacking and is often linked to low-income household *(van der Kroon et al., 2013)*. Emissions associated with the residential combustion of solid fuels are of particular concern due to its close proximity and contribution to both indoor- and ambient levels of air pollution, thus having a direct impact on the household residents as well as the surrounding community *(Rehfuess et al., 2011)*. There are numerous carcinogenic and non-carcinogenic health effects associated with HAP, and more specifically with solid fuel use within the residential setting. These effects have been investigated and reported in a number of studies *(Amegah et al., 2014; Balakrishnan et al., 2011; Barnes et al., 2009; Bates et al., 2013; Boy et al., 2002; Bruce et al., 2015; Chakraborty et al., 2014; Dherani et al., 2008; Ezzati & Kammen, 2001, , 2002;*

Fatmi et al., 2014; Kim et al., 2011; Kurmi et al., 2010; Mishra, 2003; Misra et al., 2018; Padhi & Padhy, 2008; Pope et al., 2010; Rehfuess et al., 2011; Zhang & Smith, 2007) globally.

The Constitution of the Republic of South Africa makes provisions for the protection of the environment for current and future generations. It states in Section 24 that everyone has the right to live in an environment that does not negatively impact on their health or welfare *(South Africa, 1996)*, this includes having access to clean air. South Africa is not exempt from problems associated with anthropogenic air pollution. There are a number of highly industrialised regions in South Africa which contribute significantly to the level of ambient air pollution. These impacts are not limited to urban areas. Rural regions are equally affected, however, some may even argue that people residing in these regions have a higher vulnerability due to the accumulated environmental problems present in rural areas *(Matooane et al., 2004).*

In recent years, attention has been drawn toward the air quality in densely populated low-income residential communities, both urban and rural. The residential combustion of solid fuels is considered to be the most significant contributing source, however, other sources include unpaved roads, waste burning, open biomass burning, vehicle emissions, neighbouring sources such as industries, and indoor sources not related to fuel combustion *(Engelbrecht et al., 2001, 2002; Jafta et al., 2017).* It has been found that measured ambient particulate concentration (especially during winter), within these communities, exceed the National Ambient Air Quality Standards (NAAQS). This is due to the high rate of residential combustion activities as well as the influence of shallow boundary layer *(Hersey et al., 2015)*. It is important to note that this excludes the air pollution associated with specific micro-environments, including the indoor environment of residences. This is important as a large number of people spend the majority (±19 hours per day, IQR: 14-23) of their time indoors *(Wood et al., 2012)*. This has been confirmed with the publication of the *"Strategy to Address Air Pollution in Dense Low-Income Settlements"* by the Department of Environmental Affairs (DEA) *(South Africa, 2019).*

1.2. Literature review

The measurement, characterisation and management of particulate aerosol pollution is very difficult due to its complex nature. The purpose of the literature review was to provide background information on particulate matter (PM) with regard to:

(i) the physical- and chemical properties including a review of different ambient and indoor source categories and associated element species profiles;
(ii) identifying indoor source contribution through chemical receptor modelling;
(iii) the health impacts associated with exposure; and
(iv) the regulatory approaches taken to manage air quality in South Africa.

1.2.1. Characterisation of particulate matter

Aerosols present in the atmosphere are commonly defined as suspended particles, either liquid or solid, within a gas that was emitted into the atmosphere from either natural or anthropogenic sources *(Seinfeld et al., 2006).* There are a number of parameters which affect aerosol behaviour. These properties can be physical and chemical in nature. Physical characteristics include aspects such as particle shape, size, density, distribution and concentration. The chemical characteristics take into account the chemical composition, primary-, and secondary particulate formation.

1.2.1.1. Physical properties

The term particle diameter (used to describe the size of a particle) arose from the irregular nature of both particle shape and density *(Zhang, 2005)*. There are different diameters, mentioned in the literature, namely the equivalent-, stoke-, and aerodynamic diameter. It allocates a specific size to a particle in order to characterise the behaviour and properties that are of interest within a given system *(Kulkarni et al., 2011)*. Aerodynamic diameter is the most commonly used as it standardises both the density and settling velocity of particles *(Zhang, 2005)*. The aerodynamic diameter is defined as *"a unit density sphere that has the same settling velocity as the particle" (McMurry, 2000).*

Table 1.1 Particles size distribution based on four different classification systems *(adapted from Chow et al., 2002; Wilson & Suh, 2012; Zhang, 2005)*.

System	Based on	Sub-classes	Size Fraction (µm)	Description
Modal	The observed size distributions and formation mechanisms.	Coarse	> 2.5	Usually mechanically generated.
		Fine	≤ 2.5	Generated by combustion or formed from gases and includes the nuclei and accumulation modes.
		Nuclei	≤ 0.1	
		Accumulation	> 0.1 to ≤ 2.5	Generated by the coagulation and condensation of nuclei mode particles.
Cut Point	The 50% cut point of the specific sampling device.			
Occupational	The entrance into various compartments of the respiratory system.	Inhalable	≤ 100	Enters the respiratory tract, including the head airways.
		Thoracic	≤ 10	Travels past the larynx and reaches the lung airways and the gas-exchange regions of the lung.
		Respirable	≤ 4	Gas-exchange region of the lung.
Regulatory	The legally specified sized for air quality standards.	Total Suspend Particles (TSP)	All sizes	Represents a 100% sampling efficiency.
		PM_{10}	≤ 10	Based on health considerations and particles small enough to enter the thoracic region.
		$PM_{10-2.5}$ (coarse)	≥ 2.5 to ≤ 10	
		$PM_{2.5}$ (fine)	≤ 2.5	Based primarily on epidemiological studies.

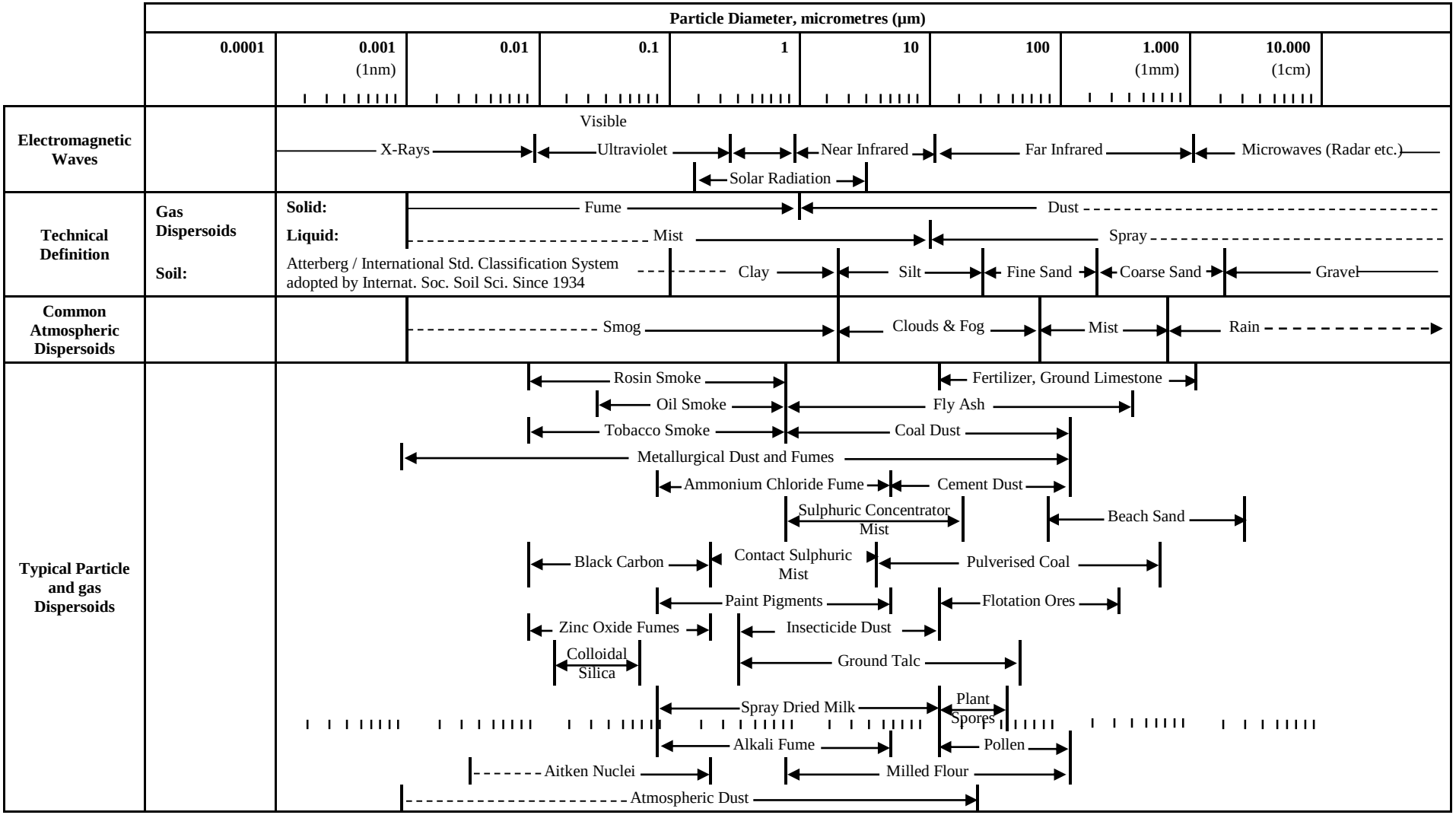
Suspended atmospheric particles are typically classified into size-distribution classes using four (4) different conventions namely mode, cut point, occupational-, and regulatory sizes *(Chow et al., 2002)*. These classification systems are summarised in *Table 1.1* above, with reference to its underlying method of classification, sub-classes of each system, associated aerodynamic size fraction in micrometre (µm), and a general description of the sub-classes.

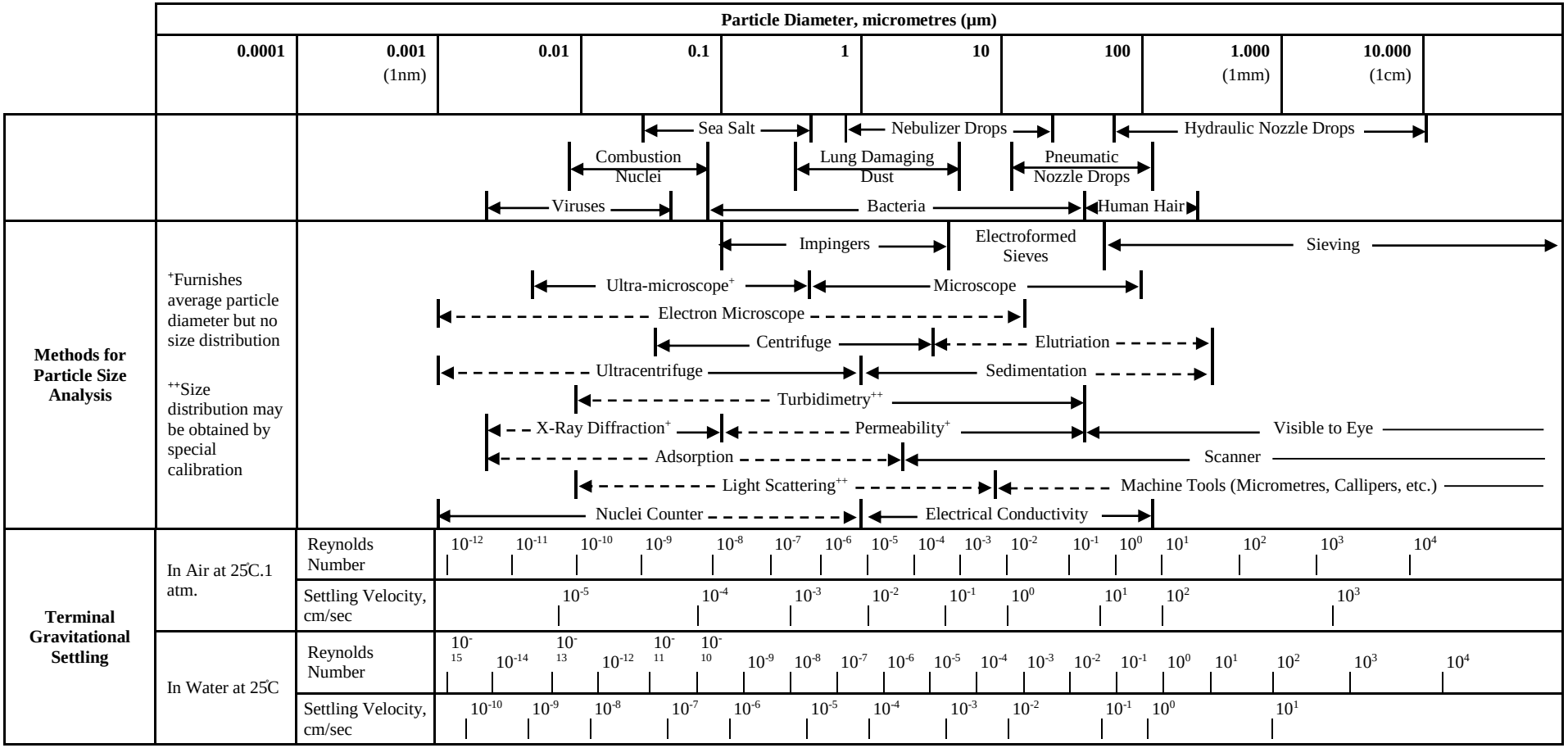
It is very important to distinguish between fine and coarse mode particles *(Seinfeld et al., 2006)* as they:

(i) originate independently from their source,
(ii) transform independent from one another,
(iii) are removed from the atmosphere by different mechanisms,
(iv) have different chemical compositions and species abundances,
(v) have varying optical properties, and
(vi) are deposited and infiltrate different parts of the respiratory system *(Fernández & Casan, 2012)*.

The $PM_{2.5}$ and PM_{10} modes are also the most commonly used in air pollution studies due to these modes being legally defined for air quality guidelines and standards *(Joss et al., 2017)*. Particle size can be further described in terms of interaction characteristics with different wavelengths of light, technical definitions, typical dispersoids, analysis methods, and gravitational settling as highlighted by *Zhang (2005)*, see *Table 1.2*.

Table 1.2 Particles according to their size ranges as described by factors such as wavelength, technical definition, typical dispersoids, analysis method, gravitational settling *(adapted from Zhang, 2005)*.




Particle Diameter, micrometres (µm)
0.0001
0.001 (1nm)
0.01
0.1
1
10
100
1.000 (1mm)
10.000 (1cm)
Sea Salt
Nebulizer Drops
Hydraulic Nozzle Drops
Combustion Nuclei
Lung Damaging Dust
Pneumatic Nozzle Drops
Viruses
Bacteria
Human Hair
Methods for Particle Size Analysis
+Furnishes average particle diameter but no size distribution
++Size distribution may be obtained by special calibration
Impingers
Electroformed Sieves
Sieving
Ultra-microscope+
Microscope
Electron Microscope
Centrifuge
Elutriation
Ultracentrifuge
Sedimentation
Turbidimetry++
X-Ray Diffraction+
Permeability+
Visible to Eye
Adsorption
Scanner
Light Scattering++
Machine Tools (Micrometres, Callipers, etc.)
Nuclei Counter
Electrical Conductivity
Terminal Gravitational Settling
In Air at 25°C.1 atm.
In Water at 25°C
Reynolds Number
Settling Velocity, cm/sec
Reynolds Number
Settling Velocity, cm/sec

1.2.1.2. Chemical properties

1.2.1.2.1. Ambient sources and associated source profiles

Particulate matter could be defined as either primary (emitted directly into the atmosphere) or secondary (formed by chemical transformation) particles. Aerosol pollutants emitted from various sources, whether natural or anthropogenic in nature, are characterised by a unique set of chemical species *(Friedlander & Keck, 1973)*. The proportions and abundance of each specie is influenced by source-specific characteristics. These include aspects such as the geographical locations, underlying geology, and the process operating conditions (such as industrial plant operations, combustion of fuels or waste, and power generation) under which emission occur *(Patil et al., 2013)*.

The level of air pollutants in the atmosphere is also influenced by a number of meteorological parameters *(Shenfeld, 1970)*. Some of the more important parameters to take into consideration include solar radiation, temperature, relative humidity, insolation, wind velocity, cloud cover, stability, and precipitation. These parameters impact on the formation *(Chen et al., 2008)*, residence times *(Vijay Bhaskar & Mehta, 2010)*, transportation and deposition of particulate aerosols *(Tyson & Preston-Whyte, 2004)*. The variation caused by the above mentioned introduces large spatial and temporal variability in aerosol distribution *(Chen et al., 2008)*.

Particulate matter speciation studies have been done in a number of countries including the United States of America *(Chow et al., 2004; Fine et al., 2001, , 2004; Labban et al., 2004; Shandilya & Kumar, 2014; Sonntag et al., 2014)*, India (Bano *et al.*, 2018; Kumar, Suresh, *et al.*, 2018; Matawle *et al.*, 2014, , 2015; Patil *et al.*, 2013), China (Bi *et al.*, 2019; Guo *et al.*, 2017; Kong *et al.*, 2011; Liu, Zhang, *et al.*, 2018; Liu, Xing, *et al.*, 2018; Ni *et al.*, 2017; Sai *et al.*, 2015; Shen *et al.*, 2016; Tian *et al.*, 2017; Wang *et al.*, 2015; Wu *et al.*, 2016; Zhang, Shen, *et al.*, 2014), and various European countries *(Alastuey et al., 2006; Alleman et al., 2010; Amato et al., 2011; Argyropoulos et al., 2013; Cesari et al., 2012; Colombi et al., 2010; El Haddad et al., 2009; Kara et al., 2014; Pey et al., 2013; Pietrodangelo et al., 2013; Schmidl, Bauer, et al., 2008; Schmidl, Marr, et al., 2008; Wåhlin et al., 2006; Yatkin & Bayram, 2008)*.

These speciated source profiles contribute to a number of existing databases. Since the early 1980s, the United States of America's Environmental Protection Agency (EPA) has led the development of a comprehensive source profile database, known as SPECIATE. The first SPECIATE database (version 3.2) was made available to users in 2002. Since then the database has been improved on a continuous basis resulting in versions 4.0 *(U.S.EPA, 2006)*, 4.2 *(U.S.EPA, 2009)*, 4.3 *(U.S.EPA, 2011)*, 4.4 *(U.S.EPA, 2014)*, 4.5 *(U.S.EPA, 2016)*, and 5.0 *(U.S.EPA, 2019*). This repository currently contains approximately 3 782 particulate emission speciation profiles for various source categories *(Simon et al., 2010)*. The European Commission made available the SPECIEUROPE database in 2015. This repository contains 287

atmospheric particulate matter emission speciation profiles specifically related to European countries *(Pernigotti et al., 2016)*. More recently China made available the China Source Profile Shared Services (CSPSS) version 1.0, with more than 500 particulate speciation source profiles *(Liu et al., 2017)*. There is no existing database of local source profiles for South Africa. Thus, most source apportionment studies use speciation profiles from existing databases that are available internationally. However, the lack of local source profiles thwarts our ability to effectively conduct source apportionment analyses as the profiles are integral to understanding local source contribution and impacts in a specific environment.

Common source profile categories include crustal soil, biomass burning, coal combustion, fugitive dust, industrial processes, vehicle emissions, and waste burning. *Table 1.3* provides elemental fingerprint examples of various sources based on a review of source speciation profile studies from various regions of the world. There are a number of common sources that contribute to particulate matter loadings in South Africa. The general characteristics of these sources are briefly described below.

Table 1.3. Element profiles based on the source contribution in percentage mass for fine ($PM_{2.5}$), coarse ($PM_{10-2.5}$), and TSP particle.

Emission Source	Fraction	Percentage Mass			
		<0.1	**0.1 to <1.0**	**1.0 to <10.0**	**≥10.0**
Natural					
Crustal Material [1, 2, 3, 4, 8, 10, 13, 14, 18]	Fine	As, Ba, Cd, Co, Cr, Cu, Hg, Mo, Rb, Sb, Se, Sn, Sr, V	Cl, Mn, Ni, Pb, S, Ti, Zn	Al, Ca, Fe, K, Mg, Na	Si
	Coarse	Ba, Cd, Cr, Cu, Ni, Pb, Rb, Sr, V, Y, Zn, Zr	Cl, Na, P, S, Ti	Ca, Fe, K, Mg, Mn	Al, Ca, Si
	TSP	V, Cr, Mn, Zn, Pb	Na, Mg, Ca, Ti, Sb, Ba	Al, K, Fe	Si
***Marine Salt** [1, 2]	Fine & Coarse	Cd, Cr, Mn, Ni, Pb, Sr, V, Ti, Ni, Zr, Ag, Sn, Sb	Al, Si, Ca, Fe, Cu, Zn, Ba, La	K, Mg	Na, Cl
Vegetative Burning [1, 3]	Fine	Br, Ca, Fe, Mn, Ni, Pb, Rb, Se, Zn	Al, S	Cl, K	
Anthropogenic					
Asphalt [2, 7]	Fine	Ba, Cd, Cr, Cu, Mn, Ni, Pb, Sr, V, Zn	K, Mg, Na	Al, Fe	Ca
	Coarse	Ag, As, Cd, Cr, Cu, Mn, Ni, Sr, V	Al, Ba, Ce, In, Mg, Pb	Fe, K, Na, Sn, Zn	Ca, Si
Agricultural Soil [1]	Coarse	Cr, Sr, Zn	Ba, Cl, Mn, S, Ti	Al, Ca, Fe, K	Si
Agricultural Waste Burning [7, 16]	Coarse	Ag, Al, As, Ba, Ca, Cd, Ce, Co, Cr, Cu, Fe, Ga, Hf, Hg, In, Lu, Mg, Mn, Mo, Na, Ni, P, Pd, Sb, Sc, Se, Sm, Sn, Sr, Th, Ti, V, W, Y, Zn	Pb, Si, Zr	K	
Brake Dust [10]	TSP	Cr	Mg, Al, S, K, Ca, Mn, Zn, Sb, Pb	Si, Ti, Cu, Ba	Fe

Table 1.3 (Continued)

Emission Source	Fraction	Percentage Mass			
		<0.1	**0.1 to <1.0**	**1.0 to <10.0**	**≥10.0**
Cement Dust/Production [13, 14]	Coarse	V, Mn, Co, Cu, Zn, As, Cd, Pb,	K, Ti	Al, Cr, Fe, Mg, Na	Ca, Si
Coal Combustion [2]	Fine	Cd, Mn, Pb, Sr	Ba, Cr, Cu, K, Mg, Ni, V, Zn	Al, Fe, Na	Ca
	Coarse	Cd, Mn, Ni, Pb, Sr	Ba, Cr, Cu, K, Mg, V, Zn	Al, Fe, Na	Ca
Coal Combustion in Stove [7]	Fine	Ag, Al, As, Ba, Ca, Cd, Ce, Co, Cr, Cu, Fe, Ga, Hf, Hg, In, Lu, Mg, Mn, Mo, Ni, Pb, Pd, Sb, Sc, Se, Si, Sm, Sn, Sr, Th, Ti, V, W, Y, Zr	P, Zn	K, Na	
	Coarse	Ag, As, Ba, Cd, Ce, Co, Cu, Ga, Hf, Hg, In, Lu, Mo, P, Pb, Pd, Sb, Sc, Se, Sm, Sn, Sr, Th, V, W, Y, Zn, Zr	Al, Cr, K, Mn, Na, Ni, Si, Ti	Ca, Fe, Mg	
Coal-Fired Power Plant [1, 7, 18]	Fine	As, Br, Cl, Cr, Ga, Mn, Rb, Se, Zr	Ba, K, Ni, P, Pb, Sr, Ti, V, Zn,	Al, Ca, Fe, S	Si
	Coarse	Ag, As, Ba, Cd, Ce, Co, Cr, Ga, Hf, Hg, In, Lu, Mg, Mn, Mo, Ni, P, Pb, Pd, Sc, Se, Sm, Sr, Th, V, Y, Zn, Zr	Cu, K, Na, Sb, Sn	Ca, Fe, Si	Al
Coal Fly Ash [3]	Fine	Rb, Mo, Y, Cr, Se, Ga, Zr, Pb, Zn, Cu, V, Mn	K, Sr, P, Ti	Ba, S, Fe, Al, Si	Ca
	Coarse	Rb, Se, Y, Ga, Ni, Cr, Pb, Zr, Zn, Cu, Mn	P, Sr, K, Ba, Ti	S, Fe	Al, Si, Ca
Cooking [15, 18]	Coarse	Cu, Mn, Pb	Ca, Cl, K, Mg, Zn	Al, Fe, Na	
Construction Dust [7, 8, 13, 14, 18]	Fine	As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, S, Sb, Se, V	Al, K, Mn, Zn	Fe, Mg, Na	Ca
	Coarse	Ag, As, Ba, Cd, Ce, Co, Cr, Cu, Ga, Hf, Hg, Lu, Mn, Mo, Ni, P, Pb, Pd, Sb, Sc, Se, Sm, Sr, Th, V, W, Y, Zr	In, Na, Ti, Zn	Al, Fe, K, Mg, Si, Sn,	Ca
Diesel Generators [7]	Coarse	Al, Ba, Ca, Cd, Co, Cr, Hg, Lu, Mg, Mn, Ni, Sc, Sr, Ti, Y, Zn, Zr	Ag, As, Ce, Fe, Ga, Hf, In, K, Mo, Na, P, Pb, Pd, Sb, Se, Si, Sm, Sn, Th, V, W		
Fuel Oil Burning [2, 7]	Fine	Ag, Al, Ba, Cd, Ce, Co, Cr, Cu, Ga, Hf, Hg, In, K, Lu, Mg, Mn, Mo, P, Pb, Pd, Sb, Sc, Se, Sm, Sn, Sr, Th, Ti, W, Y, Zr	As, Fe, Si, Zn	Ca, K, Mg, Na, Ni, V	
	Coarse	Ag, Al, As, Ba, Cd, Ce, Co, Cu, Fe, Ga, Hf, Hg, In, K, Lu, Mg, Mn, Mo, P, Pb, Pd, Sb, Sc, Se, Si, Sm, Sn, Sr, Th, Ti, W, Y, Zr	Cr, Zn	Al, Ca, Fe, K, Mg, Na, Ni, V	
Fugitive Fertilizer [7]	Coarse	Ag, Al, As, Ba, Cd, Ce, Co, Cr, Cu, Ga, Hf, Hg, Lu, Mn, Mo, Ni, Pb, Pd, Sb, Sc, Se, Sm, Th, Ti, V, W, Y, Zr	In, K, Na, Sn, Sr, Zn, Ti, W,	Ca, Fe, Mg, P, Si	

Table 1.3 (Continued)

Emission Source	Fraction	Percentage Mass			
		<0.1	**0.1 to <1.0**	**1.0 to <10.0**	**≥10.0**
Incinerator [1]	Fine	Ag, Cu, Mn, Sn, V	Al, Hg, Ti, Zn	Br, Ca, Fe, La, Pb, S, Si	Cl
Kerosene Combustion [7, 9, 11]	Fine	Ag, Al, As, Ba, Cd, Ce, Co, Cr, Cu, Ga, Hf, Hg, Lu, Mg, Mn, Mo, Ni, P, Pd, Sb, Sc, Se, Sm, Sr, Th, Ti, V, W, Y, Zr	In, Na, Pb, Si, Zn	Ca, Fe, K, S, Sn	
	Coarse	Ag, Ba, Cd, Ce, Co, Cr, Cu, Ga, Hf, Hg, Lu, Mg, Mn, Mo, P, Pd, Sc, Sm, Sr, Th, Ti, W, Y, Zr	As, Fe, In, K, Na, Ni, Pb, S, Sb, Se, Si, V, Zn	Al, Ca, Sn	
LPG Combustion [7, 9, 11]	Fine	AS, Ca, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Mo, Ni, Pb, Sb, Se, V, Zn	Al, K, Na, S		
	Coarse	Ba, Cd, Co, Cr, Cu, Ga, Hf, Hg, Lu, Mg, Mn, Mo, Ni, Pd, Sb, Sc, Sr, Th, V, Y, Zn, Zr	Ag, As, Ca, Ce, Fe, In, K, P, Pb, Se, Si, Sm, Sn, W	Al, Na	
Motor Vehicle Emissions - Gasoline [1, 3, 6, 18]	Fine	Cr, Cu, Ni, Y	Al, Br, Ca, Cl, Fe, Mn, P, Pb, Si, Zn	S	
	Coarse	Cu, Pb	Cl, K, Mn, Zn	Al, Ca, Fe, K, Na	
Motor Vehicle Emission – Light Duty Diesel [8, 18]	Fine	Al, As, Ca, Cd, Co, Cr, Cu, Hg, K, Mg, Mn, Mo, Ni, Sb, Se, Se, V	Fe, Na, Pb, Zn	S	
	Coarse	Cu, Mn, Pb	Ca, K, Mg, Zn	Al, Fe, Na, Cl	
Motor Vehicle Emission – Heavy Duty Diesel [8, 17]	Fine	Al, As, Ca, Cd, Co, Cr, Cu, Hg, K, Mg, Mn, Mo, Ni, Sb, V	Fe, Pb, Se, Zn	Na, S	
Paved Road Dust [1, 3, 7, 8, 10, 13, 14]	Fine	Ag, As, Ba, Cd, Ce, Co, Cu, Ga, Hf, Hg, In, Lu, Mo, Ni, P, Pd, Sb, Sc, Se, Sm, Sr, Th, V, W, Y, Zn, Zr	Al, Cr, K, Mn, Na, Pb, Sn, Ti	Fe, Mg, Si	Ca
	Coarse	Cr, Cu, Mn, Ni, Pb, Pb, Rb, Sr, Zr	Ba, Cl, Mg, P, S, Ti, Zn	Al, Fe, K	Ca, Si
	TSP	S, V, Cr, Mn, Co, Ni, Zn, Cd, Sb, Ba, Pb	Na, Mg, Cl, Ti, Cu, Sn	Al, K, Ca, Fe	Si
Residential Solid Fuel Combustion [9, 11]	Fine	Al, AS, Cd, Co, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Se, V	Ca, Cr, Fe, Mg, Na, S, Zn, F, Na	K	
	Coarse	Al, As, Cd, Co, Cu, Hg, Mn, Mo, Ni, Pb, S, Sb, Se, V	Cr, Fe, Mg, Zn	Ca, K, Na	
Tire Dust [10]	TSP	Mn, Co, Cu, Cd, Sn	Na, Mg, S, Cl, K, Ti, Ni, Zn, Ba, Pb	Al, Si, Ca, Fe	
Tobacco Processing [2]	Fine	Ba, Cd, Cr, Cu, Mn, Ni, Pb, Sr, V, Zn	K, Mg, Na	Al, Ca, Fe	
	Coarse	Ba, Cd, Cr, Cu, Mn, Ni, Pb, Sr, V, Zn	K, Mg, Na	Al, Ca, Fe	
Traffic Emissions [2]	Fine	Ba, Cd, Cr, Cu, Mg, Mn, Ni, Pb, Sr, V, Zn	Al, Fe, K, Na	Ca	
	Coarse	Ba, Cd, Cr, Cu, Mn, Ni, Pb, Sr, V, Zn	Al, Fe, K, Mg, Na	Ca	

Table 1.3 (Continued)

Emission Source	Fraction	Percentage Mass			
		<0.1	**0.1 to <1.0**	**1.0 to <10.0**	**≥10.0**
Unpaved Road Dust [1, 3, 5, 7, 8, 10]	Fine	Ag, As, Au, Ba, Br, Cd, Cl, Co, Cr, Cu, Ga, Hg, In, La, Mn, Mo, Na, Ni, Pb, Pd, Rb, S, Sb, Se, Sn, Sr, Tl, U, V, Zn	P, Ti	Al, K, Mg	Ca, Fe, Si
	Coarse	Ag, As, Au, Br, Cd, Co, Cr, Cu, Ga, Hg, In, La, Mo, Na, Ni, Pb, Pd, Rb, Sb, Se, Sn, Sr, Tl, U, V, Zn	Ba, Cl, Mg, Mn, P, S, Ti	Al, Fe, K	Ca, Si
	TSP	V, Cr, Co, Ni, Zn, Cd, Pb	Na, Mg, S, Cl, Ti, Mn, Cu, Sn, Sb, Ba	Al, K, Ca, Fe	**Si**
Waste Burning (Municipal) [7, 9, 11]	Fine	Al, As, Ba, Cd, Ce, Cr, Cu, Ga, Hf, Hg, Lu, Mg, Mn, Mo, Ni, P, Pb, Pd, S, Sb, Sc, Se, Sm, Sr, Th, Ti, V, W, Y, Zr	Ca, Co, Fe, In, K, Na, Si, Zn	Sn	
	Coarse	Al, As, Ba, Cd, Ce, Co, Cr, Cu, Ga, Hf, Hg, Lu, Mn, Mo, Ni, P	Fe, Mg, In, Si, Zn	Ca, K, Na, Sn	
Waste Burning (Garden) [7]	Coarse	Ag, Al, As, Ba, Cd, Ce, Co, Cr, Cu, Ga, Hf, Hg, Lu, Mg, Mn, Mo, Ni, P, Pd, Sb, Sc, Se, Sm, Sr, Th, Ti, V, W, Y, Zr	Ca, Fe, In, Na, Pb, Si, Zn	K, Sn	
Wood Combustion [2]	Fine	Al, Ba, Cd, Cr, Cu, Mg, Mn, Na, Ni, Pb, Sr, V	Fe, Zn	Ca, K	
	Coarse	Al, Ba, Cd, Cr, Cu, Mg, Mn, Na, Ni, Pb, Sr, V, Zn	Ca, Fe	K	
Wood Combustion in Stove [7]	Fine	Ag, Al, As, Ba, Ca, Cd, Ce, Co, Cr, Cu, Fe, Ga, Hf, Hg, Lu, Mg, Mn, Mo, Ni, P,, Pb, Pd, Sb, Sc, Se, Si, Sm, Sn, Sr, Th, Ti, V, W, Y, Zr	In, Na, Zn	K	
	Coarse	Ag, As, Ba, Cd, Ce, Co, Cr, Cu, Ga, Hf, Hg, Lu, Mo, Na, Ni, P, Pb, Pd, Sb, Sc, Se, Sm, Sn, Sr, Th, V, W, Y, Zn, Zr	Al, K, Mg, Mn, Si, Ti	Ca	Fe

[1]Watson et al., 1997; [2]Yatkin & Bayram, 2008; [3]Chow et al., 2004; [4]Zhang, Cao, et al., 2014; [5]Labban et al., 2004; [6]Sonntag et al., 2014; [7]Patil et al., 2013; [8]Matawle et al., 2015; [9]Bano et al., 2018; [10]Kumar et al., 2018; [11]Matawle et al., 2014; [12]Samara et al., 2003; [13]Kong et al., 2011; [14]Zhang, Shen, et al., 2014; [15]Sai et al., 2015; [16]Ni et al., 2017; [17]Liu, Zhang, et al., 2018; [18]Chen, Wang, et al., 2017

1.2.1.2.2. Indoor sources of contaminants

Indoor pollutants originate from both the indoor or ambient environment *(Fernández et al., 2013)*. These contaminants can either be biological, carcinogenic or chemical in nature *(Dales et al., 2008)*. Biological contaminants include allergens, endotoxins, as well as building-related dampness and mould. Chemical contaminants are divided into two sub-groups, namely combustion products (environmental tobacco smoke, coal and biomass fuels, carbon monoxide, nitrogen dioxide) and gases released from indoor materials (formaldehyde, volatile organic compounds, and plastic compounds). The latter is also referred to as off-gassing emissions. Carcinogens may comprise of compounds such as radon and asbestos *(Dales et al.,*

2008). A list of the most significant organic and inorganic pollutants, including the indoor pollutants most damaging to human health, can be viewed in *Table 1.4*.

Table 1.4. List of organic and inorganic pollutants including the major health-damaging pollutants from indoor sources *(Zhang & Smith, 2003)*.

Organic	Inorganic	Common Indoor air pollutant	Major indoor sources
- **Acrylonitrile** - **Benzene** - **Butadiene** - **Carbon disulphide** - **Carbon monoxide** - **1,2-Dichloroethane** - **Dichloromethane** - **Formaldehyde** - **Polycyclic aromatic hydrocarbons (PAHs)** - **Polychlorinated biphenyls (PCBs)** - **Polychlorinated dibenzodioxins (PCDDs)** - **Polychlorinated dibenzofurans (PCDFs)** - **Styrene** - **Tetrachloroethylene** - **Toluene** **Trichloroethylene Vinyl chloride**	- As - Asbestos - Cd - Cr - F^- - H_2S - Pb - Mn - Hg - Ni - Pt - V	Fine particles	Fuel/tobacco combustion, cleaning, cooking
		Carbon monoxide	Fuel/tobacco combustion
		Polycyclic aromatic Hydrocarbons	Fuel/tobacco combustion, cooking
		Nitrogen oxides	Fuel combustion
		Sulphur oxides	Coal combustion
		Arsenic and fluorine	Coal combustion
		Volatile and semi-volatile organic compounds	Fuel/tobacco combustion, consumer products, furnishings, construction materials, cooking
		Aldehydes	Furnishings, construction materials, cooking
		Pesticides	Consumer products, dust form outside
		Asbestos	Remodelling/demolition of construction materials, insulation for heating systems
		Lead*	Remodelling/demolitions of painted surfaces
		Biological pollutants	Moist areas, ventilation systems, furnishings
		Radon	Naturally occurring underground, construction materials
		Free radicals and other short-lived reactive compounds	Indoor chemistry

***Lead-containing dust from deteriorating paint is an important indoor pollutant for occupants in many households, but the most critical exposure pathways are not usually through the air.**

1.2.2. Indoor source apportionment by statistical receptor modelling methods

In order to create and evaluate source-specific control strategies one needs to have an accurate understanding of both the physical and chemical characteristics associated with particulate aerosols, where these particles might have originated, and what the contribution of individual sources are to the particulate concentration *(Cooper & Watson, 1980; Core et al., 1982)*. This is achieved through source apportionment. Source apportionment refers to a statistical analysis that uses the atmospheric concentration data and apportions them between likely contributing sources *(Viana et al., 2008)*. It is often carried out for different size fraction such as PM_1, $PM_{2.5}$, $PM_{2.5\_10}$, PM_{10}, and TSP. The analysis can be done for the concentration

of a single time-integrated aerosol sample or for the average of a collection of samples *(Viana et al., 2008)*. There are various techniques *(Figure 1.1)* that can be used for source apportionment including, the basic numerical treatment of monitored data, emission inventories, dispersion models, and receptor models *(Cooper & Watson, 1980; Core et al., 1982; Viana et al., 2008)*. The focus point of this section of the review is specifically on receptor models and its application to resolve source apportion within the indoor environment.

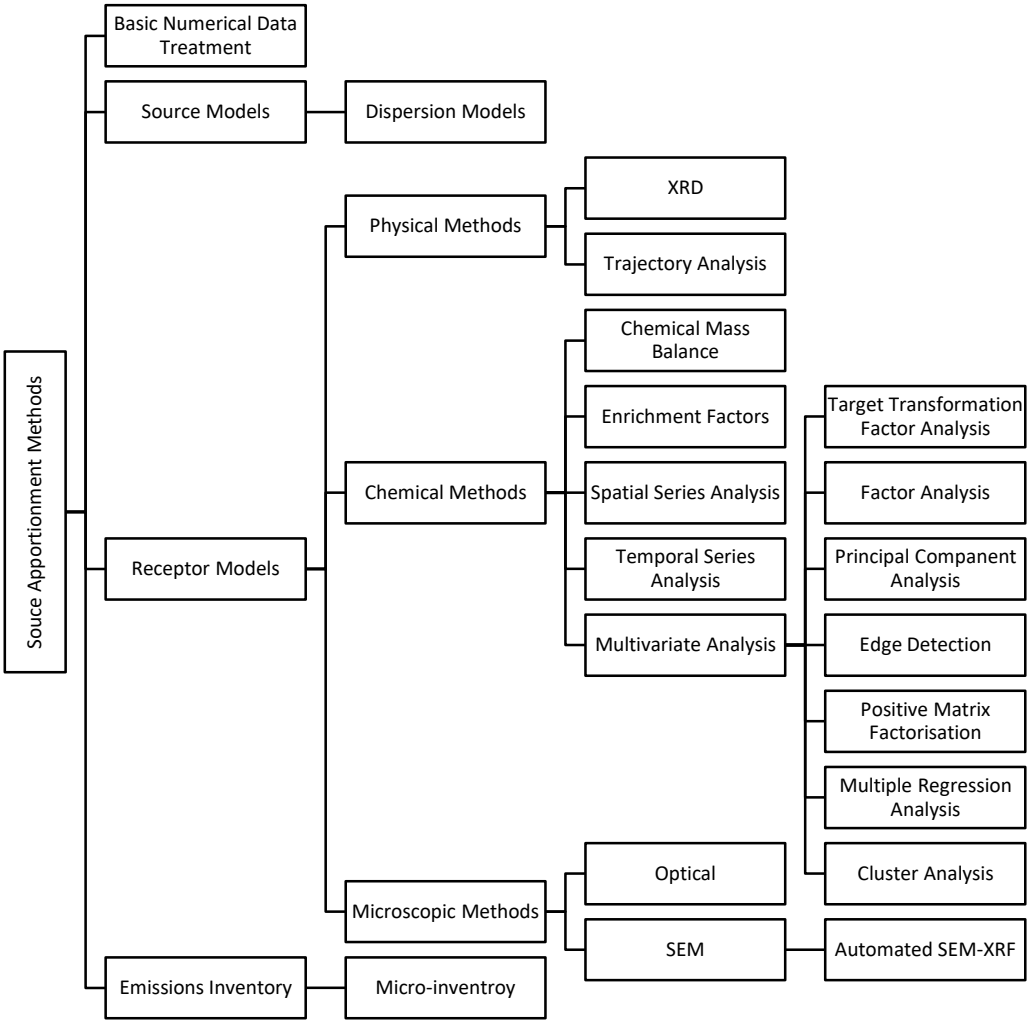


Figure 1.1 Schematic block diagram comparing different source apportionment methods and the relationship between several forms of receptor models *(adapted from Cooper & Watson, 1980; Core et al., 1982; Viana et al., 2008a).*

Numerous reviews were completed between the early 1970s and late 1990s *(Cooper & Watson, 1980; Core et al., 1982; Gordon, 1988; Henry et al., 1984; Hopke, 1991; Javitz et al., 1988; Moyers et al., 1975; Mroz & Zoller, 1975; Seigneur et al., 1999; Thurston & Lioy, 1987; Watson, 1984; Watson et al., 1989)*. These studies investigate a diverse range of receptor models and their variations. More recent reviews *(Belis et al., 2013; Hopke, 2003, , 2016; Hopke & Cohen, 2011; Pant & Harrison, 2012; Reff et al., 2007; Viana et*

al., 2008; Watson et al., 2002; Zhang et al., 2017) investigate the progress, improvements, and new developments made to receptor models. Watson and associates *(2002)* provide a detailed review of the theory and application of receptor models citing over 500 different references for the period 1959 to 2002. They found that elemental analysis is essential for receptor models, however, it is not sufficient. To further distinguish between various source types additional information is needed on ions, isotopic abundances, carbon, organic compounds, and single particle characteristic.

Receptor models are statistical source apportionment analysis methods, using both chemical and physical characteristics of aerosol pollutants measured at a specific sampling site, known as the receptor, to identify and quantify various source contributions at the receptor site *(Watson et al., 1989)*. These models are based on a number of assumptions and limitations *(Table 1.5)*. The most influential assumption made is that mass is conserved from the source to the receptor. The validity of this assumption is dependent on the sources included in the airshed as well as the model used *(Core et al., 1982)*. These models use both suspended particulate matter and gases due to the variety of available chemical species. This makes it possible to distinguish one source from another through source fingerprinting *(Watson et al., 1989)*.

Table 1.5 Assumptions and limitations associated with receptor models *(adapted from Watson, 1984)*.

	Assumptions	**Limitations**
1.	Composition of source emissions are constant.	Source compositions are not constant, they vary with changes in process inputs, loads and cycles.
2.	Components do not react with each other.	Components do react with each other and systems are not linear.
3.	There is a specific number of sources contributing to the receptor.	One rarely knows exactly how many sources are contributing to a receptor.
4.	The number of sources is equal to or less than the number of components.	There are many more sources than components which can be practically measured.
5.	The composition of all sources are linearly independent of each other.	Many sources have very similar compositions.
6.	Measurement errors are random, uncorrelated and normally distributed.	Measurement errors are not necessarily random, uncorrelated, or normally distributed.
7.	Emissions reach a uniform concentration throughout the airshed immediately upon introduction into the atmosphere.	Emissions definitely do not instantaneously reach a uniform concentration throughout the atmosphere upon leaving a source.
8.	The decay rate is linear with time.	They do not exhibit decay constants which are linear with time.
9.	Each source has just component/tracer in its composition.	Very few sources have their own unique tracer components.

Receptor models are subdivided into three (3) categories, microscopic-, physical-, and chemical methods. Chemical receptor modelling methods are reviewed and discussed briefly to provide the necessary background for the analysis used in this study. This modelling method can be divided into five (5) sub-groups (*Figure 1.1*) and includes chemical mass balance-, enrichment factor-, temporal series-, spatial

series-, and multivariate analyses. The above mentioned requires knowledge of the chemical composition of the measured aerosols as well as the possible sources *(Cooper & Watson, 1980).*

1.2.2.1. Chemical mass balance

The chemical mass balance (CMB) model has been used extensively to apportion sources *(Viana et al., 2008)*. CMB determines the impact of sources in a detailed quantitative manner. It is most appropriate to use when all sources, including their downwind characteristics, influencing the receptor are known and clearly defined *(Seigneur et al., 1999; Thurston & Lioy, 1987)*. The fundamental CMB expression is given in *Equation 1.1*:

$$C_r = \sum_{j=1}^{p} F_{rj} S_j$$

Equation 1.1. CMB receptor model *(adapted from Cooper & Watson, 1980)*.

where *Cr* is the concentration of the aerosol species measured at the receptor, *Frj* is the fraction of aerosol *r* emitted by source *j*, as measured at the source, and *Sj* is the contribution of the sources. CMB methods have been applied to various analyses of indoor air quality in the United States of America (USA) *(Adgate et al., 1998; Anderson et al., 2002; Kalaiarasan et al., 2017)*, India *(Gadkari & Pervez, 2007, , 2008; Pervez et al., 2012)*, Finland *(Kopperud et al., 2004)*, and Germany *(Gokhale et al., 2008)*.

1.2.2.2. Enrichment factors

The enrichment factor (EF) model is used to calculate the enrichment of measured chemical species in collected aerosol samples at a receptor site relative to reference profiles. The EF is calculated using *Equation 1.2*:

$$EF_i = \frac{(X_i/X_n)_{measured}}{(X_i/X_n)_{reference}}$$

Equation 1.2. Enrichment factor of aerosols relative to reference *(Cooper & Watson, 1980)*.

where *EFi* is the EF of element *i*, *n* is the reference element, $(X_i/X_n)_{measured}$ is the concentration ratio of element *i* over the reference element *n* in the measured sample, and $(X_i/X_n)_{reference}$ is the abundance ratio of element *i* over *n* in the reference source profile *(Cooper & Watson, 1980)*. Chemical species with EFs greater than one (1) are more abundant in the sampled aerosol compared to the reference material, while EFs less than one (1) suggest that the elemental component is depleted in the sampled aerosol relative to the reference material *(Moyers et al., 1975)*. Elemental species with EFs equal to one (1) indicate unity between the measured- and reference material *(Mroz & Zoller, 1975)*. This analysis requires only basic

knowledge of the chemical elemental composition of possible contributing sources. It is most useful in a region where limited source profiles are available. This method has various shortcomings as the results depend on the accuracy of the assumed reference profile composition. The method cannot be used to reliably resolve complex source mixtures where an ambient aerosol sample has multiple complex source contributions *(Cooper & Watson, 1980)*. EFs methods have been implemented in analyses of indoor air quality *(Ali et al., 2017; Buczyńska et al., 2014; Gemenetzis et al., 2006; Habre et al., 2014; Zhang, Chen, et al., 2014; Zhu et al., 2012)*. The best results use a combination of EF analysis and additional receptor modelling methods that provide supporting information for understanding the contributing sources.

1.2.2.3. Spatial and temporal series analysis

Most source apportionment studies have some sort of spatial and/or temporal association. The spatial series analysis provides an approximation of possible source contributions by comparing the observed spatial distribution of aerosol concentrations, measured simultaneously at various receptor sites, with the aerosol composition and geographical location of known emission sources within a given area. On the other hand, the temporal series analysis assumes aerosol species that show similar time dependencies at a receptor are likely to have originated from the same source *(Cooper & Watson, 1980; Watson et al., 2002)*. Similarly to the EF model, the above-mentioned correlations do not account for a quantitative determination of contributing sources. This method can be applied to either short- or long-term studies. Short-term studies provide insight into the hourly or daily variations, while long-term studies often uncover the impact of sources that occur seasonally.

1.2.2.4. Multivariate methods

The multivariate analysis methods use pattern recognition to detect the shared variability of elements across a large number of samples. This variability is used to imply possible source contributions by comparing the common elements to specific source profiles *(Cooper & Watson, 1980)*. This method is often implemented in indoor source apportionment and includes the following analyses, namely, factor analysis (FA) *(Hopke et al., 2003; Martuzevicius et al., 2008; Molnár et al., 2014; Palmgren et al., 2003; Tunno et al., 2016)*, principal component analysis (PCA) *(Ali et al., 2017; Anderson et al., 2002; Guo, 2011; Koistinen et al., 2004; Martuzevicius et al., 2008; Molnár et al., 2014; Palmgren et al., 2003; Shin & Jo, 2012; Tunno et al., 2016)*, multiple regression analysis (MRA) *(Ali et al., 2017; Yakovleva et al., 1999)*, positive matrix factorisation (PMF) *(Amato et al., 2014; Anderson et al., 2002; Bari et al., 2015; Barraza et al., 2014; Hopke et al., 2003; Huang et al., 2015; Larson et al., 2004; Liu et al., 2014; Minguillón et al., 2012; Molnár et al., 2014; Park et al., 2012; Saraga et al., 2010; Suryawanshi et al., 2016; Tunno et al., 2016; Yakovleva et al., 1999; Zhou et al., 2014; Zhu et al., 2012)*. It is difficult for a single method to distinguish between two sources that have indistinguishable signatures. Thus, it is common to use a combination of these analyses, as done by Anderson et al. *(2002)*.

Previously published literature *(Table 1.6)* has identified a large variation in the possible sources and their contribution to different indoor environments. The studies investigated the source identification of both particulate and gaseous pollutants, however, most focused on the $PM_{2.5}$ and PM_{10} size fractions. The major sources identified to contribute to indoor air quality included crustal soil, resuspended dust from indoor and outdoor activities, traffic emissions (tire wear and resuspended materials from road surface), vehicle exhaust, biomass burning, fuel combustion, building materials, cleaning products, cooking, environmental tobacco smoke, sulphate and nitrate related aerosols, and the regional ambient air.

There are a limited number of studies related to the measurement of pollutants within the indoor environments of residential homes in South Africa (Barnes *et al.*, 2006, , 2011; Elf *et al.*, 2017; Gaspar *et al.*, 2015; Jafta *et al.*, 2012; Language *et al.*, 2016; Rollin *et al.*, 2004; Sanyal & Maduna, 2000; Shezi *et al.*, 2017; Vanker *et al.*, 2015; Wernecke *et al.*, 2015). It is important to note that none of the above-mentioned studies identify possible sources or source contributions through source apportionment analysis. This is a significant shortcoming in understanding residential indoor air pollution, the impacts it may have, and the possible mitigation and management thereof.

Table 1.6 Summary of literature implementing chemical receptor models that have been applied to indoor source apportionment (1990-2018).

Reference	Study	CRM	Size Fraction	Species	Country	City	Year	Location (N)	N Samples (Time)	Possible Sources	Elements	% Contribution (μg.m^{-3})				
(Adgate et al., 1998)	I	CMB	TSP	MTE	USA	New Jersey	1992	ResH (64)	64	Indoor Air	S	17	18			
			PM_{10}	Pb						Paint	Pb, Ti, Zn, Ba,	35	34			
										Crustal Soil	Al, Si, S, Ca, K, Fe	49	50			
(Yakovleva et al., 1999)	I	PMF	PM_{10}	MTE	USA	California	1991	ResO (178)	2 (12h)	Resuspended Dust	Al, Si, K, Ca, Fe	17	3			
	O	MRA	$PM_{2.5}$							NFMO / Vehicle Emissions	Pb, Br, Zn, Fe, Mn	11	10			
	P									Secondary Sulphate	S	21	19			
										Sea-Salt	Cl	<1	<1			
										Personal Activity	Cl, Si, K, Ca	15	11			
(Anderson et al., 2002)	I	*CMB*	N/A	VOCs	USA	New Jersey	1980/1984	ResO (600)	(24h)	Vehicle Emissions	C_6H_6, C_8H_{10}	*43*	**21**	*43*	**40**	
		PCA				California	1987/1990		(24h)	Insecticide	$C_2H_3Cl_3$	*19*	**31**	*2*	**18**	
		PMF								Building Materials	$C_2H_3Cl_3$, C_8H_{10}, $C_{10}H_{22}$, $C_{12}H_{26}$,	*13*	**20**	*11*	**11**	
		UNMIX								Cleaning Products	C_2Cl_4	*9*	**13**	*12*	**8**	
										Office Air	$C_2H_3Cl_3$,, C_8H_{10}, $C_{12}H_{26}$, $C_{11}H_{24}$	*15*	**9**	*20*	**11**	
										Tap Water	CCl_4, **$CHCl_3$**, C_2Cl_4, $C_2H_3Cl_3$,	*2*	**5**	*5*	**3**	
										Primers/Sealers	$C_{10}H_{22}$, $C_{11}H_{24}$ / **C_2HCl_3**			*6*	**4**	
										Consumer Products	C_6H_5Cl, C_8H_{10} / **$C_{10}H_{16}$**			*1*	**5**	
(Palmgren et al., 2003)	I	SSA	TSP	CO	Denmark	Copenhagen	2000/2001	ResH (1)	(24h)	Non-Traffic Emissions	CO, NO_x (low)	*				
	O	TSA	PM_{10}	EC						Petrol-Diesel	CO, NO_x (high)					
		FA/PCA		MTE						Diesel	CO (low)					
		CPRM		NOx												
				OC												
(Hopke et al., 2003)	I	FA	$PM_{2.5}$	EC	USA	Baltimore	1998	ResH (1)	36 (24h)	Nitrate-Sulphate	SO_2, NO_x	1				
	O	PMF		IC				ResO (10)		Secondary Sulphate	S, NO_3^-	65				
	P	ME		MTE						Organic Carbon	OC	18				
				OC						Vehicle Emissions	OC, EC, NO_3^{-1}	16				
(Koistinen et al., 2004)	I	PCA	$PM_{2.5}$	MTE	Finland	Helsinki	1996/1997	ResH (102)	2 (24h)	Combustion	-	28				
	O							ResO (76)		Inorganic Secondary	SO_4^{2-}, NO_3^-, NH_4^+	36				
	P									Crustal Soil	Al, Si, Ca, Fe, Ti, K	27				
	W									Detergents	PCl_3/PCl_5	6				
										Seas-Salt	Cl	2				
(Kopperud et al., 2004)	I	CMB	$PM_{2.5}$	IC	USA	California	2000	ResH (1)	*4 (4-6h)*	Indoor Origin	*	*60*	*72*	*89*	*40*	**27**
	O		PM_5	MTE					**1 (24h)**	Outdoor Origin		*44*	*36*	*18*	*102*	**77**
(Larson et al., 2004)	I	PMF	$PM_{2.5}$	MTE	USA	Washington	2000/2001	ResH (16)	(24h)	Vegetative Burning	BC, S, K, Ca, Si	(4)	(5.4)			
	O			EC						Crustal Soil 1	Al, Si, S, K, Ca, Ti, Fe	(0.9)	(2.3)			
	P			OC						Cl-Rich	Cl, S, BC	(0.3)	-			
										Mobile Emissions	BC, Fe, S, K, Ca	(0.3)	(0.4)			
										Secondary	S	(2.9)	(1.3)			
(Kim et al., 2005)	I	Meff	$PM_{2.5}$	IC	Canada	Ontario	1999/2001	ResO (28)	10 (24h)	Traffic Emissions	OC, EC	13				
	O			EC						Regional Air Pollution	SO_4^{2-}	17				
	P			OC						Crustal Soil	Cl	7				
										Indoor Origin		63				

Table 1.6 (Continued)

Reference	Study	CRM	Size Fraction	Species	Country	City	Year	Location (N)	N Samples (Time)	Possible Sources	Elements	% Contribution ($\mu g.m^{-3}$)	Reference	Study	CRM	Size Fraction
(Gemenetzis et al., 2006)	I	EF	$PM_{2.5}$ PM_{10}	MTE	Greece	Thessaloniki	*	UniR (40)	1 (7h)	ETS Resuspended Dust Anthropogenic Origin	Cl, K, As, V, Co, Ni, Br Mg, Si, Ti, Fe, P S, Cl, Cu, Zn, As, Se, Br, Cd, Pb	*				
(Zhao et al., 2006)	I O P	ERM	$PM_{2.5}$	EC OC MTE	USA	North Carolina	2000/2001	ResO (38)	7 (24h) per season	Vehicle Emissions Crustal Soil Secondary Sulphate Secondary Nitrate ETS/Mixture Personal Activity Cu-factor/Resuspended Dust Cooking	OC, EC, Zn, Fe Si, Ca, Fe, Ti S NO_3^- EC, OC, K, Si, Ca, K, Fe, OC, Cl, K, Ca, Br, Zn Si, S, Cu, Ca, K, Zn, Cl OC, S, Si, Ca, Zn, Ti	9 4 23 5 10 19 1 54				
(Gadkari & Pervez, 2007)	I P	CMB	RPM	*	India	*Dabrapara* Padmanabhpur	2004	ResO >18h (9) ResO <18h (14) ResO <14h (5)	4 (24h)	Regional/Ambient Crustal Soil Road Traffic Indoor Origin	Fe, Ca, Mg, Na, K, Zn, Pb, Mn Fe, Ca, Mg, K, Mn, As Ni, Cd, Pb, Hg Fe, Ca, Mg, Na, Ni,	*0-26* *0-69* *5-78* *0-66*	0-25 0-75 0-94 0-95			
(Zhao et al., 2007)	I O P	ERM	$PM_{2.5}$	MTE IC EC OM	USA	Colorado	2002/2004	SchO (56)	(24h)	Secondary Sulphate Crustal Soil Secondary Nitrate Vehicle Emissions Cleaning Products/Tap Water Cooking ETS	S Al, Si, Ca, Fe NO_3^- OM, EC, Fe, Cl OM, Ca OM, K	9 4 3 27 <1 30 2				
(Gadkari & Pervez, 2008)	I O P	CMB	PM_5	MTE	India	Bhilai-Durg	2003	SchO (15)	16-20 (12h)	Regional/Ambient Crustal Soil Road Traffic Indoor Origin	Fe, Ca, Mg, Na, As Fe, Ca, Na, K, Fe, Ca, Mg, Na, K, Li, Zn, Ni Fe, Ca, Mg, Na,	48-73 5-38 0-1 0-22	- - 45-50 50-55	0-94 - 0-15 0-98		
(Gokhale et al., 2008)	I O P	CMB	*	VOCs	Germany	Leipzig	2005	ResO (7)	5 (24h)	Indoor Residential Regional/Ambient Indoor Office	* 	42-73 18-34 2-38				
(Martuzevicius et al., 2008)	I O	FA	$PM_{2.5}$	EC OC MTE	USA	Cincinnati	2004	ResH (6)	5 (24h) *Spring* **Fall**	Traffic Emissions Sulphate	Mn, Zn S	*(2)* *(<1)*	**(1)** **(2)**			
(Yli-Tuomi et al., 2008)	I	MEM	$PM_{2.5}$	*	Finland Germany	*Helsinki* **Amsterdam**	1998/1999	ResO (44) ResO (33)	205 (24h) 4-5 230 (24h) 6-7	LRT-Secondary Sulphate Urban Mix Oil Combustion Traffic Emissions Sea-Salt Crustal Soil K-Factor Cu-Factor Unaccounted	S S, K, Zn, Fe Ni, V FE, Cu, EC Cl Fe, Ca, K K Cu -	*35* *14* *13* *3* *2* *6* *14* *6* *7*	**41** **17** **11** **8** **3** **5** **4** **1** **9**			

Table 1.6 (Continued)

Reference	Study	CRM	Size Fraction	Species	Country	City	Year	Location (N)	N Samples (Time)	Possible Sources	Elements	% Contribution ($\mu g.m^{-3}$)	Reference	Study	CRM	Size Fraction
(Saraga et al., 2010)	I	PMF	*$PM_{2.5}$*	PAHs	Greece	Athens	2007	OffS (1)	5-7 (24h)	ETS	$C_{12}H_{12}$, $C_{13}H_{14}$, $C_{18}H_{12}$	*21*	**26**			
			PM_1					OffNS (1)		Resuspended Dust	$C_{18}H_{12}$, $C_{20}H_{12}$, $C_{24}H_{14}$	*37*	**35**			
										Oil Combustion	$C_{13}H_{10}$,	*28*	**17**			
										Gasoline Burning Vehicles	$C_{18}H_{12}$,$C_{20}H_{12}$, $C_{13}H_{10}$, $C_{16}H_{10}$	*14*	**22**			
(Guo, 2011)	I	*PCA*	*	VOCs	China	Hong-Kong	2002	ResH (100)	(24h)	Household Products	C_7H_{16}, C_7H_8, C_8H_{10}, C_8H_8, C_9H_{20}	*30*	**6**			
		APCS								Painted Wood Product	CH_3COOH, C_8H_{10}	*11*	**4**			
										Room Freshener	C_9H_{20}, $C_{10}H_{22}$, $C_{12}H_{18}$ and $C_{10}H_{16}$	*9*	**8**			
										Building Materials		*8*	**77**			
										Consumer Products	CH_2O, $C_{10}H_{16}$	*7*	**1**			
										Mothballs	$C_6H_{12}O$	*6*	**5**			
											$C_6H_4C_{l2}$					
(Minguillón et al., 2012)	I	PMF	$PM_{2.5}$	BS	Spain	Barcelona	2008	ResO (54)	2 (24h)	Sulphate	SO_4^{2-}	10				
	O			IC						Fuels/Sea-Salt	V, Ni, Na, Mg, BS	2				
	P			MTE						ETS	K, Ce, Cd, $C_{20}H_{12}$, $C_{22}H_{12}$	2				
				PAHs						Minerals	Al_2O_3, Ca, Ti, Fe, Li, Rb, Sr	2				
										Traffic Emissions	Pb, Sn, Cu, Mn, Fe	4				
										Industrial	BS, Ca, Fe, SO_4^{2-}, Pb	1				
										Unaccounted		1				
										Non-Analysed		75				
(Park et al., 2012)	I	PMF	PM_{10}	IC	Korea	Seoul	2010	TranCab (41)	(2-3hr)	Secondary Sulphate/Cl^-	SO_4^{2-}, Cl^-	9a				
				MTE						Secondary Nitrate	NO_3^-	16				
										Railroad	Fe, Mn, Cr, Cu	48				
										Crustal Soil/Resuspended Dust	Si, Mg, Cr, Ni	27				
(Pervez et al., 2012)	I	CMB	RPM	IC	India	Raipur	2009	ResH *(4)*	(24h)	Household Fuel Combustion	TC, SO_4^{2-}, Cl, NO_3, Ca	*28*	*48*	*17*	*32*	
				MTE						Industrial (Urla)	SO_4^{2-}, Cl, NO_3^-, Fe, Cr, Mn, Ni, As, Hg, V	*32*	*3*	*2*	*13*	
				TC						Industrial (Siltara)		*5*	*23*	*4*	*30*	
										Industrial (Mandir)	TOC, SO_4^{2-}, Fe, Ca, Mg, K, S	*12*	*2*	*45*	*3*	
										Traffic Emissions	TOC, SO_4^{2-}, Fe, S	*20*	*18*	*30*	*16*	
										Crustal Soil	TC, Fe, Zn	*3*	*6*	*2*	*6*	
											Fe, Al, Ca, Mg					
(Shin & Jo, 2012)	I	*PCA*	*	FORM	Korea	Daegu	*	ResH (107)	10 (24h)	Floorings	*	*30*	**25**			
	O	**APCA**		VOCs		Ulsan				Wood/Vinyl Floor Covering		*17*	**31**			
						Youngcheon				Wall Coverings		*10*	**18**			
										Adhesives		*9*	**15**			
										Paints		*5*	**11**			
(Zhu et al., 2012)	I	EF	$PM_{2.5}$	IC	China	Rural	2007/2008	ResH (3)	22 (24h)	Coal combustion	*	*21*				
	O	PMF		MTE		*Winter*				Construction Dust		*7*				
				OC		**Summer**				Biomass Burning		*24*	**31**			
										Motorcycle		*18*				
										Secondary Nitrate		*3*				
										Secondary Sulphate		*24*				
										Soil Dust		*3*	**8**			
										Secondary Aerosols			**43**			
										Road Dust			**7**			
										Gasoline Vehicle Emissions			**11**			

Table 1.6 (Continued)

Reference	Study	CRM	Size Fraction	Species	Country	City	Year	Location (N)	N Samples (Time)	Possible Sources	Elements	% Contribution ($\mu g.m^{-3}$)	Reference	Study	CRM	Size Fraction
(Amato et al., 2014)	I O	PMF	$PM_{2.5}$	EC IC MTE OC	Spain	Barcelona	2012	Sch (39)	(24h)	Sea-Salt Minerals Resuspended Road Dust Traffic Secondary Nitrate Sulphate/Organics Metallurgy Heavy Oil Org/Textile/Chalk	Na, Cl- Al, Mg, Mg, Li, Fe, Ca, Ti, Rb Ca, Fe, Cu, Sb EC, Cu, Sb, Sn, Fe NO_3^- SO_4^{2-}, NH_4^+ Zn, Pb, Cd, Mn, Cu EC, OC, V, Ni OC, Sr	2 17 4 13 4 11 3 1 45				
(Barraza et al., 2014)	I	PMF	$PM_{2.5}$	EC OC MTE	Chile	Santiago	2012	ResH (47)	1 (48h)	Vehicle Emissions Resuspended Dust Sulphates Cooking/ETS Cleaning/Cooking Indoor Dust	EC, OC, Al, Si, S, Ca, Ti, Mn OC, Mn, Cu S EC, OC, K Cl Al, Si, Ca, Ti, Fe	26 13 16 28 11 7				
(Buczyńska et al., 2014)	I O	EF MC	$PM_{2.5}$	MTE IC	Belgium	Antwerp	2008	ResH (1)	(24h) *Episode* **Non-episode**	Smoke Crustal Matter Sea-salt Ammonium Non-sea-salt-Sulphate Nitrate Other Elements	Non-crustal K Al, Si, Ca, Ti, Fe Na^+, Cl^- NH_4 SO_4^{2-}, Na^+ NO_3 As, Cr, Cu, Mn, Ni, Pb, Sr, V, Zn	*<2* *<5* *<5* *10* *30* *<5* <1	**<2** **<10** **10** **5** **15** **<5** **<1**			
(Habre et al., 2014)	I O	EF Meff	$PM_{2.5}$	EC OC MTE	USA	New York	2008/2009	ResO (37)	5-10 (24h)	Cooking/cleaning/ETS Photochem.l/Metals/Combustion Dust/Crustal Soil/Metals	OC, Si, Cl, K, Fe EC, Br, Mn, Pb, Ni, Ti, V, S Al, Zn, Fe, Si, Ca	46 28 26				
(Hasheminassab et al., 2014)	I O	CMB	$PM_{2.5}$	MTE OC	USA	Los Angeles	2005/2006	ResH (3)	126 (24h)	Vehicle Emissions Sulphate Resuspended Dust WSOM Wood Smoke Ship Emissions Unaccounted	* 	39 18 11 1-13 3 <1 7				
(Liu et al., 2014)	I	PMF	*	Carbonyls BTEX	China	Beijing	2009	ResH (128)	2 (1h)	Building Material/Paint Cleaning Products Out Emission Incursion 1 Out Emission Incursion 2 Particle Board/Flooring	C_6H_6 C_7H_8 C_2H_4O, C_3H_6O C_8H_{10} CH_2O	14 16 37 17 16				
(Molnár et al., 2014)	I O P	PMF FA	$PM_{2.5}$	MTE	Sweden	Gothenburg	2002/2003	ResO (30)	1 (24h)	LRT Traffic Emissions Local Combustion Indoor Heated Sources Indoor Resuspension Sea-Salt/Resuspended Dust	S, V, Ni, Br Fe, Mn, Cu, Zn, BC BC, K, Zn, Br, Pb BC, S, Cl, K, Cu S, Cl, K, Ca, Fe Cl, K, Ca, Ti, V	(<5) (<1) (<2) (<2) (<1) (<2)				

Table 1.6 (Continued)

Reference	Study	CRM	Size Fraction	Species	Country	City	Year	Location (N)	N Samples (Time)	Possible Sources	Elements	% Contribution ($\mu g.m^{-3}$)	Reference	Study	CRM	Size Fraction
(Zhang, Chen, et al., 2014)	I	EF	$PM_{2.5}$	EC	China	Shandong	2013	UniB (1)	3 (6hr)	Trace Species		*<5*	**<10**			
		MB		OC					*Haze*	Ammonium Sulphate	$(NH_4)_2SO_4$	*55*	**40**			
				IC					**Normal**	Ammonium Nitrate	NH_4NO_3	*25*	**<5**			
				METEO						Elemental Carbon	EC	*<5*	**<5**			
										Organics		*30*	**26**			
										Crustal Soil	Al, Si, Mg, Fe, Ca, Na	*<10*	**10**			
(Zhou et al., 2014)	H	PMF	$PM_{2.5}$	MTE	Ghana	Accra (Urban)	9	ResH (80)	(48h)	Aged Biomass	KCl, K_2SO_4	39-62	*(200)*	**(300)**		
				BC	Gambia	*Banjul (Peri-Urban)*		ResH (154)	(72h)	Fresh Biomass Burning	K, Cl, S, BC		*(<20)*	**(150)**		
					Gambia	**Basse (Rural)**		ResH (49)		Sea-Salt	Na, Cl, S	<10	*(<10)*	-		
										Resuspended Dust	Al, Si, Mg, Ca, Fe	12-33	*(<20)*	**(80)**		
										Crustal Soil	Al, Si, Mg, Ti, Mn, Fe	13-21	*(<10)*	**(<10)**		
										Solid Waste Burn	Br	0-12				
(Bari et al., 2015)	I	PMF	*	VOC	Canada	Edmonton	2010	ResH (26)	7 (24h)	Households Products	See Referenced Article	44				
	O									Fragranced Consumer Products		2				
										Building Material		6				
										Floor/Wall Coverings		2				
										Paint		3				
										Deodorizers		8				
										Fuel Evaporation		2				
										Tap Water/Cleaning Products		4				
										Combustion Processes & ETS		11				
										Oil/Gas Industry		10				
										Traffic Emissions		3				
										Gasoline production and storage		4				
										Industrial /Vehicle Emissions		2				
(Huang et al., 2015)	P	PMF	$PM_{2.5}$	WSOC	China	Yunnan	2008/2009	ResO (81)	1-3 (24h)	Mobile	BC, C_nH_{2n+2}	13				
				OC						Cooking	sterols, n-alkanedioic acids, $C_{18}H_{34}O_2$	36				
				PAHs						Secondary Organic Aerosols		1				
										Wood Combustion	n- alkanoic acids, $HO_2C(CH_2)nCO_2H$, BC	4				
										Pyrolysis Combustion		3				
										Plant Waxes	WSOC, $C_6H_{10}O_5$	7				
											PAHs					
											C_nH_{2n+2}					
(Suryawanshi et al., 2016)	I	PMF	$PM_{0.6}$	Metals	India	Kanpur	2013/2014	UniRB (3)	(24h)	Coal Combustion	Fe, Ba, Ca	22				
									98 Total	Wall Dust	Ca, Cu	26				
										Wooden Furniture/Paper	Ca, Cr, Fe, Mg, Pb	25				
										ETS	Ca, Ni, Mg, Cu	10				
										Soil Particles	Mg, Cr, Cu, Ba, Ni	18				
(Tunno et al., 2016)	I	FA	$PM_{2.5}$	MTE	USA	Pittsburgh	2011/2012	ResH (21)	7 (24h)	Smoking/Cooking/Steel Making	BC, Ca, Fe, Zn, Mn, Pb	*43*	**48**			
		PMF					*Summer*			ETS/Vehicle Emissions	Cd, K, La, P, Tl	*20*	**18**			
							Winter			Coal Emi/Brake-tire	As, Sb/Cr, Mo, Sb	*12*	**12**			
										Resuspended Dust/Cooking	Al, Ca	*7*	**6**			
										Coal	S, Se	*5*				

Table 1.6 (Continued)

Reference	Study	CRM	Size Fraction	Species	Country	City	Year	Location (N)	N Samples (Time)	Possible Sources	Elements	% Contribution ($\mu g.m^{-3}$)	Reference	Study	CRM	Size Fraction
(Ali et al., 2017)	I	PCA APCA MRA EF	PM_{10}	Metals	Malaysia	Selangor	2015	UniB (2) *Building 1* **Building 2**	(8h)	Crustal Source Indoor-Induces Urban Origin Crustal Soil Combustion Biogenic Anthropogenic Unaccounted	Fe, Mn, Cr, Ni Pb, Cu Al, Cd Zn Ni, Fe Mn Zn	*20* *8* *7* *6* *59*	**3** **21** **6** **4** **66**			
(Chen, Jahn, et al., 2017)	P O	Meff	$PM_{2.5}$	EC IC OC	China	Guangzhou	2011	ResO (11)	9-12 (24h)	Regional Air Pollution Traffic Emissions Resuspended Dust Biomass Burning Other	SO_4^{2-} EC Ca^{2+}, Mg^{2+} $C_6H_{10}O_5$ -	50 9 6 2 33				
(Kalaiarasan et al., 2017)	I O	CMB	$PM_{2.5}$	MTE IS	India	Mangalore	*	Sch *(4)*	7 (8h)	Paved Road Dust Soil Dust Gas Vehicle Emissions Diesel Vehicle Emissions Marine Fuel Oil Combustion Unpaved Road Dust Open Burning	* 	*14* *4* *7* *71* *4* 	*3* *4* *81* *1* *11* 	*21* *2* *3* *60* *12* *2*	*3* *55* *19* *23* 	

Note:

*****Information not available

Study Relationship:

I – Indoor, **O** – Outdoor, **P** – Personal, **W** – Workplace

Chemical Receptor Model (CRM):

APCS - Absolute Principal Component Scores, **CMB** – Chemical Mass Balance, **CPRM** –Constrained Physical Receptor Model, **EF** – Enrichment Factors, ERM – Extended Receptor Model, **MB** – Mass Balance Methods, **MC** – Mass Closure, **Meff -** Mixed Effects Model, **MEM** – Multi-linear Engine Model, **MRA** – Multiple Regression Analysis, **PCA** – Principal Component Analysis, **PMF** – Positive Matrix Factorisation, **SSA** – Spatial Series Analysis, **TSA** – Time Series Analysis

Size Fraction:

RPM – Respirable Particulate Matter, **TSP** – Total Suspended Particulates

Species:

BS – Black Smoke, **EC** – Elemental Carbon, **FROM** – Formaldehyde, **IC** – Inorganic Components, **METEO** – Meteorological Parameters, **MTE** – Major/Trace Elements, **OC** – Organic Carbon, **OM** – Organic Matter, **PAHs** – Polycyclic Aromatic Hydrocarbons, **TC -** Total Carbon, **VOCs** – Volatile Organic Compounds

Locations:

ResH – Residential Homes, **ResO** – Residential Occupant, **Sch** – Schools, **SchO** – Scholar at School, **TranCab** – Train Cabin, **UniB** – University Building, **UniRB** – University Residential Building

Sources:

LRT – Long Range Transport, **NFMO** – Nonferrous Metal Operations, **WSOM** – Water-Soluble Organic Carbon

1.2.3. Particulate matter exposure in South African low-income communities

Health-damaging air pollution caused by various processes follows a specific environmental exposure pathway. This pathway, as seen in *Figure 1.2*, indicates the starting point as the source followed by the emissions resulting from the source, the concentration of the emitted pollutants, the exposure experienced over a specific time period, the actual dose to an individual, and finally the associated health effects. The effect of air pollution on health is not specifically linked to the concentrations of the pollutant, but rather to the pollution dose received by an individual's exposure (the actual concentration breathed) *(Ho et al., 2017)*. The health effects are directly linked to the microenvironment in which the dose is received, therefore, it is important to conduct measurements within the exact environment where exposure occurs *(Smith, 1993)*.

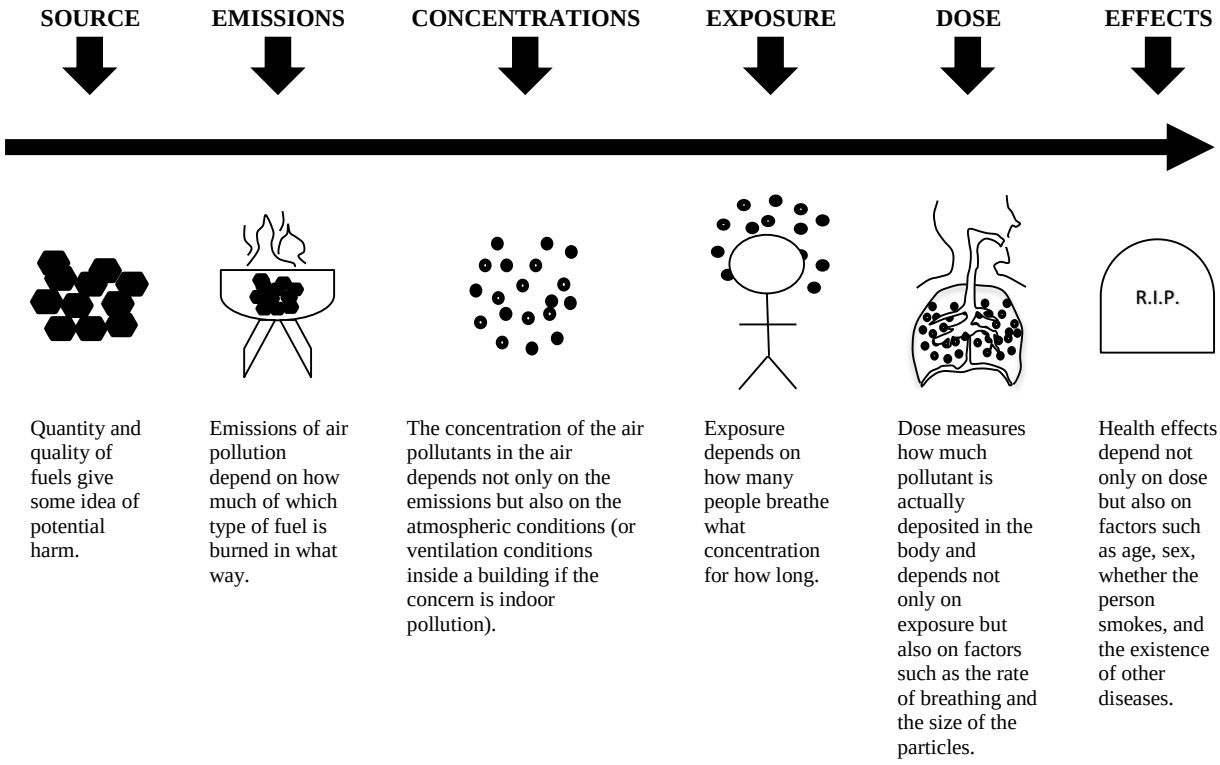


Figure 1.2 The conception environmental pathway for health-damaging air pollution. Measurement and control of health-damaging air pollution can be initiated at any of these stages *(adapted from Smith, 1993)*.

Research priorities in South Africa focus on three main areas, namely, exposure (measurements, equipment), health effect (basic, epidemiological, clinical), and interventions (improved cooking stoves, social interventions, fuel types, effects) that could be applied to mitigate and reduce impacts *(Kurmi et al., 2010)*.

1.2.3.1. Health effects associated with exposure

The link between high concentrations of air pollution and epidemiological effects was established by the early 1970s. By 1979 a comprehensive review *(Holland et al., 1979 cited by Pope, 2000)* was published on the relationship between air pollution and health. It concluded that high levels of particulate air pollution had a significant impact on human health, however, studies conducted by Shy (1979); Bates (1980); and Ware et al. (1981) *(cited by Pope, 2000)* linked up low- to moderate concentrations of air pollution to health effects. The health effects of particulate air pollution have been reviewed in detail by a number of researchers *(Vedal, 1997; Ware et al., 1981)*. More than 150 published epidemiological studies were conducted by the year 2000. The epidemiological effects of air pollution will be discussed briefly, with reference to more recent studies published from the year 2000 onwards.

Most epidemiological studies focus on the effects associated with the acute exposure to pollutants rather than the chronic exposure, however, the effects linked to chronic exposure may have a larger impact when considering the public health significance as a whole. The thought behind this is that repeated long-term exposure increases the associated risk, while short-term exposure has the ability to exacerbate existing diseases related to the cardiovascular- and respiratory systems *(Brunekreef & Holgate, 2002; Pope, 2000)*.

There are two main types of diseases associated with particulate and gaseous pollutants, namely respiratory and non-respiratory diseases *(Kim et al., 2011; Perez-Padilla et al., 2010)*. Respiratory diseases include upper and lower respiratory infection *(Dherani et al., 2008; Dhimal et al., 2010; Po et al., 2011; Rehfuess et al., 2009; Shen et al., 2009)*; chronic obstructive pulmonary disease *(Kurmi et al., 2010; Lin et al., 2009; Po et al., 2011)*; tuberculosis *(Kan et al., 2011)*; lung cancer *(Galeone et al., 2008; Lin et al., 2009)* and asthma *(Mahalanabis et al., 2002)*. Non-respiratory illnesses include low birth weight *(Amegah et al., 2014; Pope et al., 2010);* infant mortality *(Pope et al., 2010)*; and cardiovascular disease *(Fatmi et al., 2014; Lee et al., 2012; McCracken et al., 2012)*.

The findings from South African air pollution exposure- and epidemiological studies which were published between 2000 and 2018 are summarised in *Table 1.7*. There were a total of forty-six (46) studies identified during the review. These were subdivided based on the study design which included cross-sectional studies (20), reviews (6), cohorts (4), intervention-based studies (4), health risk assessment (HRA) studies (3), comparative risk assessment (CRA) studies (3), case studies (3), feasibility studies (2), and a single panel study. A large number (twenty-four (24)) of the studies did not include any quantitative measurement of air pollution exposure, thus relying on a proxy to determine exposure. Twenty-two (22) studies incorporated quantitative measurements in the form of ambient pollutant monitoring (eight (8) studies), indoor pollutant monitoring (eleven (11) studies), and a combination of both ambient and indoor pollutant monitoring in three (3) studies. The monitored pollutants include PM, SO_2, NO, NO_2, CO, and VOCs.

There have been a few review articles focussing on health effects of exposure to air pollution. The first of which was *Wichmann & Voyi (2005)*, wherein local studies published prior to June 2005 were critically reviewed to identify links between exposure and harmful effects, as well as pinpointing possible methodological limitations. This review identified the need to prioritise quantitative intervention studies. In 2009, *Barnes et al. (2009)* investigated the relationship that exists between the prevalence of acute lower respiratory infections (ALRI) in children and the type of household energy used. The aforementioned showed that children are two to four times more likely to experience ALRIs in households that actively use polluting fuels. The third, *Barnes (2014)*, considered the possible reduction in indoor air pollution exposure that could occur as a result of behavioural interventions. The review indicated potential exposure reduction ranging from 31% to 94%. In a 2015 systematic review by *Jafta et al. (2015)*, a link was made between environmental tobacco smoke (ETS) exposure and increased tuberculosis (TB) infection in children younger than fifteen (15) years of age. The most recent review by *Shezi and Wright (2018)*, provided evidence of the negative impact on respiratory health caused by household air pollution.

Table 1.7 Findings from studies on air pollution exposure (indoor and ambient) and associated health/epidemiological outcomes within South Africa (2000-2018).

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Sanyal & Maduna, 2000)	Prospective Cohort	Extend the scope of investigations conducted elsewhere and to concentrate on the levels of indoor gaseous pollutants and their impact, if any, on respiratory ailments among children.	Households from the Ku-Ntselamnzi community in the district of Victoria East in the Eastern Cape Province of South Africa during February 1995 and December 1996.	115 Households (A: 50 very low income; B: 40 low income, C: 25 middle income)	Indoor CO, NO_2 and SO_2 (6-hr in morning and afternoon)	Average CO in cooking areas of A, B, and C were 180 (148-420, SD 107), 118 (66-199, SD 72), and 67 (47-121, SD 41) $mg.m^{-3}$, respectively. NO_2 higher in living areas and SO_2 higher in cooking areas. Recurring acute respiratory infections were prevalent among children in A and B.	Limited scope not including measurements of ambient pollutants.
(Muller et al., 2003)	Health Risk Assessment	Quantify the health risk for people living in a densely populated informal settlement, related to kerosene use.	Households in Cato Crest community within Durban metropolitan area, Kwa-Zulu Natal Province, South Africa.	69 Households	US EPA HRA framework. Questionnaire survey. Indoor NO_2 and VOC measurements in 14 houses.	24-hr NO_2 poses a potential risk to a few households. Benzene poses health risks to >50% of households. Adult, child, and infant exposure 14-hr, 12-hr, and 14-hr, respectively.	No other sources considered. Lack of continuous monitoring for variability.
(Barnes et al., 2004)	Intervention Study	Investigated the acceptability and feasibility (of four indoor air pollution reduction behaviours.	Households (with children <5) in two un-electrified rural and impoverished villages in the Tribal-Delareyville magisterial district in the North West Province of South Africa.	30 Households	Pre-intervention interviews in winter 2002 Post-intervention interview 4 weeks later.	Improving stove maintenance and reducing solid fuel-burning periods proved to be difficult for most. The main focus should be child location and ventilation practices.	Behaviour influenced by the presence of researchers. Lack of continuous monitoring for variability.
(Ehrlich et al., 2004)	Cross-sectional Study	Determine the prevalence and predictors of chronic bronchitis.	National household survey of adults in South Africa, a middle-income country.	South African Demographic	1998 National health survey	Risk factors were prior to TB infection, smoking, occupational exposure, domestic exposure to smoky fuel and being underweight.	Bias in self-reporting. No use of quantitative exposure data.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Rollin et al., 2004)	Feasibility Study	Assess the suitability of South African rural villages due to be electrified, for the purposes of undertaking a large-scale study of the impact of reductions in indoor air pollution on acute lower respiratory infections.	Households in three rural settlement in the North-West Province, South Africa during summer 2000.	52 un-electrified households 53 Electrified households	Structured questionnaires Indoor and personal respirable PM and CO.	Mean respirable PM in un-electrified and electrified homes are 162 and 77 $\mu g.m^{-3}$. CO ranges from 0.36 to 20.95 ppm in un-electrified and 0 to 11.8 ppm in electrified homes.	No ambient measurements included.
(Barnes et al., 2005)	Feasibility Study	Comparison of observations and questionnaire interview with video analysis in rural South African villages.	Households in two un-electrified rural and impoverished villages in the Tribal-Delareyville magisterial district in the North West Province of South Africa.	40 Households	Observations winter 2001 Questionnaire interview and video analysis winter 2003	Video analysis, results show that observations may underestimate the number of time children spend very close to fires (<1.5m) Questionnaire interviews offer more accurate assessments, at expense of a detailed behavioural analysis	Limited video observation due to a village not being electrified. Methods not concurrently used in the same research population.
(Wichmann & Voyi, 2005)	Critical Review	Examine the evidence from local studies for associations between air pollution and adverse health along with critical reviews for methodological limitations.	MEDLINE search up to June 2005	14 studies focusing on air pollution epidemiology (excluding active smoking and internal dose)	Review	No study established an exposure-response curve – impossible to use these results in risk-assessment studies Recommend conducting quantitative intervention studies alongside analytical studies	Studies are prone to systematic and random errors limiting validity and precision.
(Barnes et al., 2006)	Intervention Study	Reporting on the effectiveness of promoting outdoor cooking in a poor rural South African community to reduce ill-health caused by kitchen smoke.	Two impoverished villages in Mafikeng local municipality, North-West Province, South Africa.	219 Households (98 intervention and 121 control)	Pre- and post-intervention interviews. CO with Dräger passive diffusion tubes (24-hr) Meteorology data.	Outdoor burning increased from 24.5% to 45.9% for intervention and 25.6% to 42.2% for control group. CO reduced by 26% in the intervention and increased 15% in the control group.	Possible Hawthorne Effect Limited pollutants monitored.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Wichmann & Voyi, 2006a)	Cross-sectional Study	Association between household solid fuel use and ALRI.	Children (<5years) with ALRI who formed part of the 1998 SADHS	2651 Households 4679 Children	Questionnaire Survey	2/3 of children lived in households using polluting fuel 19% suffered from acute lower respiratory illness 27% more likely to suffer from LRI	Confounding variable is additive and not multiplicative.
(Wichmann & Voyi, 2006b)	Cross-sectional Study	Association between household fuel combustion and mortality.	Children between 1 and 59 months (≤5years) who formed part of the 1998 SADHS	2828 Houses 3556 Children	Questionnaire Survey	65% lived in rural areas using a combination of clean and polluting fuels. Polluting fuels cause increased risk of mortality of 2.22 (95% CI=1.22, 4.04).	Proving causation is difficult as mortality and determinants are measured simultaneously.
(Balmer, 2007)	Intervention Study	Presents information collected during a baseline energy survey in an electrified urban township in South Africa, and outlines the way in which coal is used and purchased by poor households	Vosman community near Witbank, Mpumalanga Province, South Africa.	142 Interviews	Questionnaire Interviews	92% of households use coal Ave household size ~5 persons ~81% earn <R1000 per month Coal stoves (majority) and Imbawuala Bought from local coal merchants – low quality	No quantitative exposure measurements. Coal use is used as a proxy for exposure.
(Norman, Barnes, et al., 2007)	Comparative Risk Assessment	Estimate the burden of respiratory ill health in South African children and adults in 2000 from exposure to indoor air pollution associated with household use of solid fuel.	Census 2001 to derive the proportion of households using solid fuel.	Children <5 years Adults >30 years	WHO CRA methodology	20% exposed to indoor smoke from solid fuels 2489 deaths (95% CI: 1672-3324) or 0.5% (95% CI: 0.3-0.6) of all deaths in 2000 60963 DALYs (95% CI: 41170-81246) or 0.4% of all DALYs (95% CI: 0.3-0.5) ~90% of this burden occurred in the black African population	Lack of local epidemiological data.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Norman, Cairncross, et al., 2007)	Comparative Risk Assessment	Quantify the mortality burden attributed to urban outdoor air pollution in South Africa in 2000.	Urban metropolitan areas including Cape Town, Johannesburg, Durban, and Port Elizabeth.	2000 Children <5 years Adults >30 years	Ambient $PM_{2.5}$ and PM_{10} (2000-2003). WHO CRA methodology.	Estimated 3.7% of national mortality from cardiopulmonary disease and 5.1% attributable to cancers of the trachea, bronchus and lung in adults aged 30 years and older, and 1.1% of mortality from ARIs in children under 5 years of age.	The study area is limited to urban areas resulting in underestimation of the burden attributable to risk factors.
(Kistnasamy et al., 2008)	Cross-sectional Study	Examines the prevalence of symptom-defined asthma and nonspecific bronchial hyperreactivity and its relationship with ambient air pollutant concentrations.	Primary schools situated near industrial areas in Durban, KwaZulu-Natal, South Africa.	248 Students	Ambient monitoring of SO_2, CO, PM_{10}, NO, NO_2, and total reduced sulphur. Individual questionnaire and household survey. Bihourly student logs.	Odds of developing bronchial hyper-reactivity and persistent asthma was 0.64 (95% CI: 0.32 - 1.28) among the children with one or more smokers and 1.13 (95% CI: 0.61 - 2.09) for children who lived in households with non-smokers.	Does not address the causation of asthma. Short period intensive health data. Uses only ambient air pollution data.
(Barnes et al., 2009)	Review	Reviews evidence of the association between household energy, indoor air pollution and child ALRI.	PubMed, Google Scholar, and Electronic Thesis and Dissertation Database	68	Critical review.	Children 2 – 4 times more likely to suffer ALRI in households using polluting fuels; ~1400 annual child deaths.	-
(Norman et al., 2010)	Comparative Risk Assessment	Describes the health impact of exposure to four selected environmental risk factors.	Urban metropolitan areas	6 Areas	WHO CRA methodology for the year 2000	25% of all ALRI for children <5 years attributed to indoor and outdoor air pollution DALYs Effect of lead exposure, indoor/urban air pollution and tobacco: 78.1% lung cancer, 73.5% of COPD in males and 61.3% in females.	Lack of local data for risk exposure leads to the use of extrapolated data from other countries.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Barnes et al., 2011)	Quasi-experimental intervention study	Evaluate a community counselling intervention on stationary levels of PM_{10} and carbon monoxide (CO), as well as CO, measured on children younger than five.	Households in the impoverished villages of Makgabane and Tsunyane, in the North West Province of South Africa.	36 Household (intervention) 38 Households (control)	Baseline questionnaire interview (winter). Follow-up questionnaire interview (12 months later). Indoor filter sampling (24-hr) of respirable particles. Co by Dräger passive diffusion tube (24-hr)	Both groups showed improvement, but the intervention group performed better. Median reductions associated with the intervention were: PM_{10} =57%, CO =31% and CO (child) =33% amongst households that burned indoor fires.	Control group showed evidence of a possible Hawthorne Effect. Unable to capture continuous variability. Small sample with clustering in villages.
(du Preez et al., 2011)	Cross-sectional Study	Examine the dose-response effect of ETS exposure on the risk of M. tuberculosis infection in children in a high TB burden setting from December 2007 to June 2009.	Children (3-15 years) based in impoverished urban communities in Cape Town, who had contact with an adult starting clinic-based anti-TB treatment in the preceding 3 months were recruited.	196 Children	A questionnaire assessing demographics, TB exposure, ETS and biomass fuel exposure.	From the 196 children: 24% exposed to a single smoker, 63.3% exposed to multiple smokers, 49.5% were M. TB infected.	Limited conclusions regards causality, further longitudinal studies required.
(Peltzer et al., 2011)	Cross-sectional Study	Estimate the prevalence and identify correlates of second-hand tobacco smoke (SHS) through the Secondary analysis of the Global Youth Tobacco Survey conducted in South Africa.	Non-smoking school-going adolescents (aged 11-18 years).	6412 adolescents	A two-stage cluster sample design was used to produce representative data from active and passive smoking data.	ETS exposure: 25.7% at home, 34.2% outside of the home, and 18.3% both at home and outside of the home.	Bias due to self-reporting.
(Wright et al., 2011)	Cross-sectional Study	Understand the impacts of exposure to air pollution and related human health in low-income community living in the Highveld Priority Area.	KwaGuqa, Mpumalanga Province, South Africa during September and October 2010.	1003 Households	Questionnaire Survey Ambient TSP, PM_{10}, $PM_{2.5}$, SO_2, NO_2, Pb, Hg, and Mn.	Ambient pollutants were not in excess of national standards. Some cases of sinusitis and asthma.	Lack of indoor measurements.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Jafta et al., 2012)	Cross-sectional Study	Understand the relationship between allergens and childhood asthma, between May 2004 and September 2005.	Households of children (mainly asthmatics) who took part in the South Durban Health Study	135 Households	Observation Survey of the households. Sampling and analyses of settled dust. Airborne fungal sampling.	House dust allergens, Der f1 and Der p1 exceeded concentrations associated with risk of sensitization and exacerbation of asthma in 3% and 13%, respectively, of the sampled homes, while Bla g1 exceeded guidance values in 13% of the homes.	Sample size of the sub-study limits ability to observe relationships and account for interactions among variables. Home assessments were conducted in different season influencing observations.
(Reddy et al., 2012)	Longitudinal Cohort Study	Evaluates fluctuations in the forced expiratory volume in relation to lagged daily averages of ambient air pollutants (SO_2, NO_2, NO, and PM10) while considering genotype as an effect modifier over four seasons from 2004 to 2005.	Indigenous African children, between 9 and 11 years old who formed part of the South Durban Health Study.	129 Children	Questionnaires surveying demographics and symptoms. 3 Week Phases: Bihourly spirometry; Ambient monitoring of NO_2, NO, SO_2 and PM_{10}; Genotyping my multiplex PCR	25% showed evidence of bronchial hyper-reactivity. 3% reported having symptoms of persistent asthma. 25% reported symptoms of mild intermittent asthma. GSTP1 decreases the capacity to mount an effective response to oxidative stress.	Focus in only on ambient air pollution data, no indoor air quality measurements incorporated.
(Wichmann & Voyi, 2012)	Case-crossover study	Association between daily PM_{10}, SO_2 and NO_2 levels and daily RD, CVD and CBD mortality.	All mortality cases in Cape Town metropolitan municipality during 2001-2006.	149 667 mortality cases	A time-stratified approach using conditional logistic regression analysis.	Excess mortality risk between: PM_{10} and RD (1.1%; CI:-1.1,3.3), CVD (1.7%; CI:−0.1, 3.5), CBD (3.2%; CI:0.3, 6.2). NO_2 and RD (1.7%; CI:-1.3,4.7), CVD (2.6%; CI:0.2, 5.0), CBD (6.6%; CI:2.4, 11.0). SO_2 and RD (-0.7%; CI:-4.5,3.3), CVD (3.3%; CI:0.1, 6.5), CBD (5.3%; CI:0.0, 10.9)	Focus in only on ambient air pollution data, no indoor air quality measurements incorporated.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Naidoo et al., 2013)	Cross-sectional Study	Examine associations between ambient air pollutants and respiratory outcomes among schoolchildren in Durban, South Africa.	Children from 7 schools in four areas in South Durban (industrial) and three in North Durban (non-industrial), additionally asthmatic children from grades 3 – 6 in the same schools were recruited between 2004 and 2005.	341 Children	Interviews with children and their caregivers. Pulmonary function by spirometry. Skin-prick allergen tests. Ambient monitoring of SO_2 NO_x, $PM_{2.5}$ and PM_{10}.	Symptoms prevalence consistent with asthma of any severity was 32.1%. Covariate-adjusted prevalence higher among schools in the south than among those in the north for persistent asthma (12.2% v. 9.6 %) and marked airway hyperreactivity (AHR) (8.1% v. 2.8%). SO_2 resulted in increased risk of marked AHR (95% CI: 0.98 – 4.66; p=0.056)	Self-reported symptoms. No indoor pollutant measurements.
(Ayo-Yusuf et al., 2014)	Cross-sectional Study	Assessed exposure to SHS from several sources among non-smoking adults during 2010	Adults (≥16 years) who participated in the South African Social Attitudes Survey in 2010.	3094 Adults	Secondary data analyses of data on active and passive smoking.	55.9% of non-smokers reported exposure to SHS from at least one source (18.4% at work, 25.2% at home, 33.4% at a restaurant, and 32.7% at a bar).	ETS is used as a proxy for exposure. Self-reported.
(Barnes, 2014)	Review	Investigate the impact of behavioural change interventions to reduce indoor air pollution.	Published studies spanning 1983 to 2013.		PUBMED, MEDLINE, PsycLIT, PsycINFO, ERIC, Google Scholar, Science Direct, Web of Science and the Cochrane Library.	Potential to reduce indoor air pollution exposure by 20%–98% in laboratory settings and 31%–94% in field settings.	Based on studies that are methodologically weak. Little or no underlying theory
(Thabethe et al., 2014)	Health Risk Assessment	Assessing the human health risks posed by exposure to PM_{10} among a low socio-economic community.	Residents of a low-income community (eMbalenhle) near Secunda in Mpumalanga, South Africa.	Community	HRA framework applied. Ambient PM_{10} monitoring (1 month) during winter (August 2010) and summer (February 2011).	Exposed to higher concentrations of PM_{10} during winter with an average 24-h exposure of 157.37 $\mu g.m^{-3}$.	No indoor measurements used in HRA.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Shirinde et al., 2014)	Cross-sectional Study	Investigating the association of wheeze, a symptom of asthma with indoor and outdoor air pollution sources specifically ETS, residential fuel use, transportation to school and the frequency of trucks passing near homes in urban areas between February and June 2012.	Students aged between 12 and 14 years from 16 randomly selected schools in Thembisa and Kempton Park in the Ekurhuleni Metropolitan Municipality	3424 Children	Questionnaire survey	Exposure: ETS at school was associated with wheeze (OR 1.22 95% CI: 1.03- 1.45). Gas for residential heating, the likelihood of wheeze increased by 47% (OR 1.47 95% CI: 1.15-1.88). Truck increase likelihood of wheeze (OR 1.32 95% CI: 1.01-1.73).	Self-reported. Exclusion of video questionnaire data. No quantitative air pollution exposure assessment. Lack of various source inclusion.
(Albers et al., 2015)	Cross-sectional Study	Examines respiratory health outcomes and associated risk factors in children living in a part of South Africa characterised by high levels of air pollution.	Student aged between 9 and 11 years from 6 randomly selected schools in eMalahleni and Middelburg, Mpumalanga.	627 Children	Questionnaire survey	Prevalence of respiratory ill-health symptoms was 34.1%. Elevated among children from households using non-electrical fuels v. electricity for cooking (43.9% v. 31.6%) and heating (37.8% v. 29.0%).	Self-reported.
(Gaspar et al., 2015)	Cohort Study	Evaluation of potential predictors of home contamination and its relationship to serum DDT levels.	Mothers participating in the VHEMBE study, a birth cohort investigating exposures and health effects from the use of IRS for malaria control from September 2012 to January 2013.	50 Households	Indoor dust samples collected using hard surface wipe and analysed by gas chromatography-mass spectrometry. Maternal Blood (10mL)	Higher detection of o,p′-DDT, p,p′-DDE, and p,p′-DDD in dust and serum samples collected in previously sprayed buildings.	Low detection frequency in dust despite being in an area with the historic use of DDT for IRS. Self-reporting of malaria control spray history.
(Jafta et al., 2015)	Systematic Review & Metal Analysis	Investigate the relation between childhood TB and exposure to ETS and biomass fuel smoke.	Published studies between 1953 and 2014 where the study population includes children (<15 years) investigating the association between TB and indoor air pollution.	8 Studies	PubMed, Web of Science and CAB	Exposure to ETS is associated with TB infection and TB disease (OR 1.9, 95%CI 1.4–2.9) among exposed compared to non-exposed children.	Limited studies reviewed thus no conclusions drawn on causality.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Nkosi et al., 2015)	Cross-sectional Study	Investigate the association between proximity to mine dumps and prevalence of chronic respiratory disease in people aged 55 years and older,	Elderly persons situated within 1- 2 km (Exposed) and 5 km (unexposed) from mine dumps.	2397 Persons	Questionnaire Survey	Exposed elderly had a significant association with asthma (OR= 1.57), chronic bronchitis (OR=1.74), chronic cough (OR=2.02), emphysema (OR=1.75), pneumonia (OR=1.38) and wheeze (OR =2.01).	Proximity used as a proxy for exposure No evidence of causality. Differential participation rate between exposed and unexposed.
(Nkosi et al., 2015)	Cross-sectional Study	Investigates the prevalence, association between community proximity to mine dumps, and current wheeze, rhinoconjunctivitis, and asthma among adolescents from May to November 2012.	Students aged 13 to 14 years in communities in urban areas attending school 1-2 km (exposed) from mine dumps and those living >5 km (unexposed) away from the mine in the Gauteng and North-West provinces of South Africa.	3641 Children	Questionnaire Survey	Living close to mine dumps had an increased likelihood of current wheeze OR 1.38 (95% CI: 1.10-1.71), rhino-conjunctivitis OR 1.54 (95% Cl 1.29-1.82) and a protective association with asthma OR 0.29 (95% CI: 0.23- 0.35).	Self-reported. No quantitative exposure measurements. Bias due to differential participation rate between exposed and unexposed.
(Reddy et al., 2015)	A multistage stratified cluster of a cross-sectional study.	Estimating the prevalence of tobacco use in the adult SA population according to certain demographic variables, and identify the factors influencing cessation attempts among current smokers.	Adults ≥18 years of age from 10 000 households in all 9 provinces who participated in the South African National Health and Nutrition Examination Survey (SAHANES-1) in 2012.	13897 Adults	Questionnaire Survey data on tobacco smoking was extracted from the SAHANES-1 data pool.	17.6% (95% CI: 6.3 - 18.9) currently smoke tobacco of the 29.2% are males and 7.3% females.	Active smoking was used as a proxy for exposure as no quantitative measurements were included.
(Shirinde et al., 2015)	Cross-sectional Study	Investigate the association between traffic-related air pollution and allergic rhinitis, current rhino-conjunctivitis and hay fever symptoms amongst children between February and June 2012.	Students aged 12 to 14 years from 16 randomly selected schools in Thembisa and Kempton Park in the Ekurhuleni Metropolitan Municipality.	3424 Children	Questionnaire Survey	High prevalence of allergic rhinitis symptoms. Traffic-related pollution plays a role in the prevalence of allergic rhinitis symptoms.	Self-reported. Used confounding variables. Used traffic density as an indicator of traffic pollution.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Vanker et al., 2015)	Cohort Study	Describe the home environment and measure indoor air pollution in the Drakenstein Child Health Study.	Pregnant women (20– 28 weeks' gestation) located in the Drakenstein sub-district of the Western Cape, South Africa, March 2011 to May 2014.	633 Mothers	Self -reported Questionnaires and urine samples. Home visits/evaluations. Indoor air monitoring of PM_{10}, CO (24-h) and CO_2, SO_2, VOCs (2 weeks)	31% active smokers and 44% passive smokers. PM_{10} of 33.1 $\mu g.m^{-3}$ (below ambient standard). Benzene 5.6 $\mu g.m^{-3}$ (above ambient standards). Benzene and NO_2 linked with solid fuels. Increased benzene and CO in winter.	Single measurement point in the home and might not account fully for IAP occurring in other areas of the home. Instruments gave average concentrations and thus underestimates peak exposures.
(Wernecke *et al.*, 2015)	Case Study	Gain an understanding of the particulate matter concentrations a person living in a typical household in a low-income settlement in the South African Highveld is exposed to during winter 2014.	KwaDela, Mpumalanga Province, South Africa.	1 Household	Measurements included indoor and personal PM_4 and ambient $PM_{2.5}$ and PM_{10} from 7 to 19 August 2014.	Mean outdoor $PM_{2.5}$ and PM_{10}, indoor and personal PM_4 concentrations were 27±18 and 48±122 and 17±23 and 16±7 $\mu g.m^{-3}$, respectively. A high correlation between indoor and personal concentrations.	No health outcomes assessed. Single household case study.
(Language *et al.*, 2016)	Case Study	Quantify and characterise indoor and ambient PM in a low-income settlement located on the South African Highveld.	KwaDela, Mpumalanga Province, South Africa during winter (2013, 2014) and summer (2014, 2015).	23 Households	Measurements included indoor and personal PM_4 and ambient $PM_{2.5}$ and PM_{10}	Mean indoor PM_{10} range between 99 - 102 $\mu g.m^{-3}$ (winter) and 50 and 66 $\mu g.m^{-3}$ (summer). Mean indoor PM_4 range between 175 - 190 $\mu g.m^{-3}$ (winter) and 56 and 117 $\mu g.m^{-3}$ (summer).	No health outcomes assessed.
(Amegah & Agyei-Mensah, 2017)	Narrative Review	Outline international policy instruments, measures for addressing urban air pollution and its associated health impacts in Sub-Saharan Africa.	Sub-Saharan Africa	-	Ambient air quality monitoring and management systems	Accra and South Africa have the best air management programmes in the region, however, requires continual improvements and engagement from WHO and UN programmes.	No quantitative measurements or health outcomes included.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Elf et al., 2017)	Cross-sectional	Association between HAP and the occurrence of TB in a high HIV-prevalence setting.	All adults (≥ 18 years) and children (7-17 years) living in the same household as the index TB case, including the index cases themselves in townships surrounding Klerksdorp, North-West Province of South Africa in 2012.	96 Adults 28 Children 53 Households	A household survey assessing fuel use. Individual questionnaires assessing tobacco use and ETS exposure. Passive air nicotine monitors in each house for 14 day period.	Homes with a history of TB compared to those without previous TB, both second-hand smoke (83% vs. 65%, respectively) and solid / kerosene fuel use for more than 1 h/day (27% vs. 21%, respectively) were more prevalent.	Small sample size limits the detection of statistical differences between households with or without a history of TB.
(Jafta et al., 2017)	Cross-sectional Study	Characterise and develop predictive models for concentrations of three air pollutants in homes of children participating in a childhood TB study.	Children (<15 years) residing in eThekwini Municipality diagnosed with TB (cases) and without TB (controls).	246 Children and homes 114 Homes subjected to monitoring.	Home walkthrough checklist Active indoor PM_{10} monitoring for 24-h period (105 homes). Passive indoor SO2 and NO2 for 2 to 3 week period (82 homes).	Mean indoor PM_{10}, NO_2 and SO_2 were 64 µg.m^{-3} (range 6.6–241.0); 19 µg m^{-3} (range 4.5–55.0) and 0.6 µg m^{-3} (range 0.005–3.4), respectively. Largest contributors to the PM_{10} predictive model were the type of housing structure, number of smokers, and type of primary fuel used.	Limited to the indoor environment - no outdoor measurements on days of indoor sampling. Single 24-hr sample per house.
(Morakinyo et al., 2017)	HRA	Assess the health risks associated with exposure to particulate matter (PM_{10}), sulphur dioxide (SO_2), nitrogen dioxide (NO2), carbon monoxide (CO) and ozone (O_3).	The industrial production area of Pretoria West area in Gauteng Province of South Africa.	2014 ambient data from South African Weather Service and South African Air Quality Information System.	HRA framework	Mean annual PM_{10}, SO_2 and NO_2 were 48.3±43.4, 18.68±25.4 and 11.50±11.6 µg.m^{-3}. Infants and children are at higher risk.	The assessment focuses on ambient exposure only, no indoor measurements included.
(Nkosi et al., 2017)	Cross-sectional Study	Examined exposure of asthmatic children to indoor respirable dust at exposed and unexposed schools in October 2012.	Children, including 10 asthmatics 13-14 years of age from five schools within 1- 2 km (Exposed) and 5 outside 5 km (unexposed) from mine dumps.	100 Children (50 exposed and 50 unexposed)	Personal air sampling in the breathing zone of 10 asthmatics. Outdoor SO_2 and PM_{10} were measured for 8-h at each school.	Indoor respirable dust in the classroom for exposed (0.17 mg.m^{-3}) and unexposed (0.01 mg.m^{-3}) children with asthma at each school.	Small sample size. The study was only conducted in a single spring season.

Table 1.7 (Continued)

Reference	Study Design	Aim	Population/Setting	Sample Size	Method	Findings	Limitation
(Shezi et al., 2017)	Cross-sectional Study	Model indoor levels of $PM_{2.5}$ using household characteristics, occupant activities, and nearby outdoor sources.	Household of pregnant females in the Durban metropolitan area that are participants of the Mother and Child in the Environment.	300 Households	Standardised walkthrough questionnaire. Indoor $PM_{2.5}$ filter sampling (24-hr).	$PM_{2.5}$ levels ranged from 1.4 to 162.0 $\mu g.m^{-3}$. Crowding, dwelling type, household emissions (incense, candles, cooking), and smoking practices were factors associated with an increase in $PM_{2.5}$ levels, while room magnitude and natural ventilation factors were associated with a decrease in the $PM_{2.5}$ levels.	No outdoor measurements. Meteorological factors were not included in the model. Aspect such as penetration efficiency, deposition rate, and air exchange was not studied.
(Mentz et al., 2018)	Panel Study	Association between daily respiratory symptoms and daily variability in ambient pollutant (NO_2, NO, SO_2, CO, O_3 and PM_{10}) exposures.	Schools in Merebank, Wentworth, Bluff and Lamontville communities in Durban.	4 School 423 Students per school 74260 total observations	Interviews Symptom Logs Generalised estimating equation modes	Cough risk: $ORPM_{10}$: 1.02e1.07 $ORSO_2$: 1.05e1.11 $ORNO_2$: 1.00e1.14 ORNO: 1.04e1.09	Lack of personal and indoor measurements. Self-reported data.
(Shezi & Wright, 2018)	Narrative Review	Review recent evidence of HAP and associated respiratory health outcomes in South Africa.	PubMed, Web of Science, Science Direct and Google Scholar Publish papers between 2005-2017	27 Articles 4 HAP vs respiratory health 10 HAP 13 Ambient AQ	Quasi-systematic review of the South African evidence on HAP and associated respiratory health outcomes.	Cross-sectional study design prevalent in the South African context. No studies report concentration response functions. Mainly reports on combustion generated variables.	Very few studies to critically evaluate. Inter-comparison of findings difficult due to heterogeneity in study design, target population, and health outcomes of interest.

ALRI - Acute Lower Respiratory Infection; **AQ** – Air Quality; **CBD** – cerebrovascular disease; **CI** – Confidence Interval; **CRA** – Comparative Risk Assessment; **CVD** – Cardiovascular diseases; **ETS** – Environmental Tobacco Smoke; **HAP** – Household Air Pollution; **HRA** – Health Risk Assessment; **IAP** – Indoor Air Pollution; **RD** – Respiratory Diseases; **SADHS** – South African Demographic Health Survey; **SHS** – Second-hand Tobacco Smoke, **TB** – Tuberculosis

The main motivation behind regulating air pollution is the undeniable impact it has on the environment and human health. The history of air quality management in the South African context is discussed in further detail below.

1.2.3.2. History of air quality management in South Africa: policies and legislation

In recent years environmental law has grown rapidly within the legal discipline. This growth is attributed to both global and local concerns about the increasing evidence of environmental degradation associated with unchecked development and industrialisation. In South Africa, environmental law is sourced from both international-, common-, statute-, and customary laws, as well as the South African Constitution *(Glazewski, 2000)*.

A chronological timeline of the development of international conventions and protocols as well as South African policies, legislation, and regulations applicable to air pollution management in South Africa, between 1965 and 2019, is summarised in *Table 1.8*.

There are numerous international collaborations in the form of conventions and protocols of which the main purpose is to improve air quality and reduce impacts on the environment and human health. South Africa has adopted a number of these resolutions, including the Vienna Convention for the Protection of the Ozone Layer,1985 *(United Nations Environment Programme, 2001)*; Montreal Protocol on Substances that Deplete the Ozone Layer, 1987 *(United Nations Environment Programme, 2000)*; United Nations Framework Convention on Climate Change, 1992 *(United Nations, 1992)*; Framework Convention on Climate Change: Kyoto Protocol, 1997 *(United Nations, 1998a)*; and most recently the Framework Convention on Climate Change: Paris Agreement, 2015 *(United Nations, 2015)*. The legislation and policies most critical to the management of air quality in South Africa are discussed in further detail.

Table 1.8 Chronological timeline of international conventions, -protocols, and South African legislation and policies relating to air pollution management (1965-2019).

Year	Date (dd/mm)	Title	International	South Africa	NEMA	NEMAQA	Source
1965	17/04	Atmospheric Pollution Prevention Act (Act no. 45 of 1965)		√			*(South Africa, 1997)*
1979	13/11	Geneva Convention on Long-range Transboundary Air Pollution	√				*(United Nations, 1979)*
1984	28/09	Geneva Protocol on Long-term Financing of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe	√				*(United Nations, 1984)*

Table 1.8 (Continued)

Year	Date (dd/mm)	Title	International	South Africa	NEMA	NEMAQA	Source
1985	22/03	Vienna Convention for the Protection of the Ozone Layer	√				*(United Nations Environment Programme, 2001)*
	08/07	Helsinki Protocol on the Reduction of Sulphur Emissions on their Transboundary Fluxes by at least 30 per cent	√				*(United Nations, 1985)*
1987	26/08	Montreal Protocol on Substances that Deplete the Ozone Layer	√				*(United Nations Environment Programme, 2000)*
1988	01/10	Sofia Protocol concerning the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes	√				*(United Nations, 1988)*
1991	18/11	Geneva Protocol concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes	√				*(United Nations, 1991)*
1992	04/06	United Nations Framework Convention on Climate Change (the FCCC)	√				*(United Nations, 1992)*
1994	14/06	Oslo Protocol on Further Reduction of Sulphur Emissions	√				*(United Nations, 1994)*
1996	18/12	The Constitution of the Republic of South Africa (Act no. 108 of 1996)		√			*(South Africa, 1996)*
1997	11/12	Framework Convention on Climate Change: Kyoto Protocol	√				*(United Nations, 1998a)*
1998	15/05	White Paper on the Environmental Management Policy of the Republic of South Africa		√			*(South Africa, 1998a)*
	24/06	Aarhus Protocol on Persistent Organic Pollutants (POPs)	√				*(United Nations, 1998b)*
	24/06	Aarhus Protocol on Heavy Metals	√				*(United Nations, 1998c)*
	27/11	The National Environmental Management Act (Act no. 107 of 1998)			√		*(South Africa, 1998b)*
	01/12	White Paper on the Energy Policy of the Republic of South Africa		√			*(Department of Minerals and Energy, 1998)*
1999	30/11	Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone	√				*(United Nations, 1999)*
2000	17/03	The White Paper on Integrated and Waste Management for South Africa		√			*(South Africa, 2000)*
2005	24/02	National Environmental Management: Air Quality Act (Act no. 39 of 2004)				√	*(South Africa, 2004)*
2006	21/04	Declaration of the Vaal Triangle Air-Shed Priority Area in terms of section 18(1) of the National Environmental Management: Air Quality Act (Act no. 39 of 2004)				√	*(South Africa, 2006)*

Table 1.8 (Continued)

Year	Date (dd/mm)	Title	International	South Africa	NEMA	NEMAQA	Source
2007	11/09	The National Framework for Air Quality Management in South Africa				√	*(South Africa, 2007a)*
	23/11	Declaration of the Highveld Priority Area in terms of section 18(1) of the National Environmental Management: Air Quality Act (Act no. 39 of 2004)				√	*(South Africa, 2007b)*
2009	28/05	Vaal Triangle Priority Area AQMP				√	*(South Africa, 2009a)*
	29/05	Vaal Triangle Priority Area AQMP Implementation Regulations				√	*(South Africa, 2009b)*
	18/12	Amended – 1998 Aarhus Protocol on Persistent Organic Pollutants (POPs)	√				*(United Nations, 2010)*
	24/12	National Ambient Air Quality Standards				√	*(South Africa, 2009c)*
2010	18/06	Environmental Impact Assessment Amendment Regulations			√		*(South Africa, 2010a)*
	02/07	Model Air Quality Management By-Law for easy adoption and adaption by municipalities			√		*(South Africa, 2010b)*
	30/07	Commencement of Environmental Impact Assessment Regulations			√		*(South Africa, 2010c)*
	30/07	Commencement of the Environmental Management Framework Regulations			√		*(South Africa, 2010d)*
2012	02/03	Highveld Priority Area AQMP				√	*(South Africa, 2012a)*
	04/05	Amended – 1979 Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone	√				*(United Nations, 2013a)*
	15/06	Declaration of the Waterberg National Priority Area in terms of section 18(1) of the National Environmental Management: Air Quality Act (Act no. 39 of 2004)				√	*(South Africa, 2012b)*
	29/07	National Ambient Air Quality Standards for $PM_{2.5}$				√	*(South Africa, 2012c)*
	13/12	Amended – 1998 Aarhus Protocol on Heavy Metals	√				*(United Nations, 2013b)*
2013	11/10	Regulations Prescribing the Format of the Atmospheric Impact Report				√	*(South Africa, 2013a)*
	01/11	Declaration of a Small Boiler as a Controlled Emitter and establishment of Emission Standards				√	*(South Africa, 2013b)*
		National Dust Control Regulations				√	*(South Africa, 2013c)*
	22/11	Listed Activities and Associated Minimum Emissions Standards				√	*(South Africa, 2013d)*
	29/11	Amendment to the 2007 National Framework for Air Quality Management in the Republic of South Africa				√	*(South Africa, 2013e)*

Table 1.8 (Continued)

Year	Date (dd/mm)	Title	International	South Africa	NEMA	NEMAQA	Source
2014	28/03	Declaration of Temporary Asphalt Plants as a Controlled Emitter and Establishment of Emissions Standards				√	*(South Africa, 2014a)*
	19/05	National Environmental Management: Air Quality Amendment Act 20 of 2014				√	*(South Africa, 2014b)*
	11/07	Regulations Regarding Air Quality Dispersion Modelling				√	*(South Africa, 2014c)*
	24/10	Draft National Air Quality Appeal Regulations				√	*(South Africa, 2014d)*
	04/12	Environmental Impact Assessment Regulations, 2014			√		*(South Africa, 2014e)*
		Listing Notice 1: List of activities and competent authorities identified in terms of section 24 (2) and 24D			√		*(South Africa, 2014f)*
		Listing Notice 2: List of activities and competent authorities identified in terms of section 24 (2) and 24D			√		*(South Africa, 2014g)*
		Listing Notice 3: List of activities and competent authorities identified in terms of section 24 (2) and 24D			√		*(South Africa, 2014h)*
2015	02/04	National Atmospheric Emissions Reporting Regulations				√	*(South Africa, 2015a)*
		Amendments to the Regulations Prescribing the Format of the Atmospheric Impact Report 2013				√	*(South Africa, 2015b)*
	12/06	Draft National Greenhouse Gas Emission Reporting Regulations				√	*(South Africa, 2015c)*
		Draft regulations prescribing the atmospheric emission license processing fee				√	*(South Africa, 2015d)*
		Amendments to the list of activities which result in atmospheric emission which have or may have a significant detrimental effect on the environment, including health, social conditions, economic conditions, ecological conditions or cultural heritage				√	*(South Africa, 2015e)*
	18/09	Declaration of a Small-Scale Char and Small-Scale Charcoal Plants as controlled emitters and establishment of emission standards				√	*(South Africa, 2015f)*
	20/11	Regulations pertaining to the Financial Provision for Prospecting, Exploration, Mining or Production Operations			√		*(South Africa, 2015g)*
	09/12	Waterberg Bonjala Priority Area Air Quality Management Plan				√	*(South Africa, 2015h)*

Table 1.8 (Continued)

Year	Date (dd/mm)	Title	International	South Africa	NEMA	NEMAQA	Source
2016	11/03	Regulations prescribing the atmospheric emissions license processing fee				√	(South Africa, 2016a)
	18/03	Regulations for the Procedure and Criteria to be followed in determination of an administrative fine in terms of section 22A of the act				√	(South Africa, 2016b)
		Air Quality Offset Guidelines (Section 24J (a))			√		(South Africa, 2016c)
	22/04	Framework Convention on Climate Change: Paris Agreement	√				*(United Nations, 2015)*
	24/06	Draft Strategy to address Air Pollution in Dense Low-income Settlements: For comments				√	(South Africa, 2016d)
	09/09	Proposed amendments to Financial Provisioning Regulations, 2015			√		*(South Africa, 2016e)*
2017	03/04	National Greenhouse Gas Emission Reporting Regulations				√	*(South Africa, 2017a)*
	07/04	Amendment of the environmental impact assessment regulations listing notice 3 of 2014			√		*(South Africa, 2017b)*
		Amendment of the environmental impact assessment regulations listing notice 2 of 2014			√		*(South Africa, 2017c)*
		Amendments to the environmental impact assessment regulations, 2014			√		*(South Africa, 2017d)*
		Amendment of the environmental impact assessment regulations listing notice 1 of 2014			√		*(South Africa, 2017e)*
	13/04	Draft procedure to be followed in applying for environmental authorisation for large scale wind and solar photovoltaic developments			√		*(South Africa, 2017f)*
		Draft notice of intention to adopt Gauteng Provincial Environmental Management Framework standards and exclusion of activities			√		*(South Africa, 2017g)*
	30/06	Proposed regulations to phase-out the use of persistent organic pollutants			√		*(South Africa, 2017h)*
	20/07	Procedures and criteria for regulating fines in terms of section 24G			√		*(South Africa, 2017i)*
	21/07	Declaration of Greenhouse Gases as priority pollutants				√	*(South Africa, 2017j)*
		National Pollution Prevention Plans Regulations				√	*(South Africa, 2017k)*
2018	09/02	National guideline on minimum information Requirements for Preparing Environmental Impact Assessments for Mining Activities that Require Environmental Authorisation			√		*(South Africa, 2018a)*
	20/04	Regulations pertaining to the Financial Provision for Prospecting, Exploration, Mining or Production Operations			√		*(South Africa, 2018b)*

Table 1.8 (Continued)

Year	Date (dd/mm)	Title	International	South Africa	NEMA	NEMAQA	Source
	22/05	Amendment of the National Pollution Prevention Plans Regulations, 2017				√	*(South Africa, 2018c)*
	25/05	Notice of Intention to Amend the List of Activities which result in Atmospheric Emission which have or may have a significant detrimental effect on the environment, including health, social conditions, economic conditions, ecological conditions or cultural heritage				√	*(South Africa, 2018d)*
		Draft National Dust Control Regulations				√	*(South Africa, 2018e)*
		Notice of intention to amend the 2012 National Framework for Air Quality Management in the Republic of South Africa				√	*(South Africa, 2018f)*
	08/06	Climate Change Bill, 2018: For public comment		√			*(South Africa, 2018g)*
	13/07	Corrections to the Environmental Impact Assessment Regulations and Listing Notices, 2014			√		*(South Africa, 2018h)*
	24/07	Proposed Regulations to Phase-out the use of Persistent Organic Pollutants			√		*(South Africa, 2018i)*
2019	17/05	Strategy to address air pollution in dense low-income settlements				√	*(South Africa, 2019)*

The principal act regulating air pollution in South Africa was the Atmospheric Pollution Prevention Act no. 45 of 1965 (APPA). The act was aimed at establishing a National Air Pollution Advisory Committee and working towards the prevention of air pollution by implementing best practicable means. It also focused on industrial-, smoke-, dust-, and vehicular emissions *(South Africa, 1997)*. The sought-after environmental quality could not be obtained with APPA as it had numerous shortcomings, such as, i) being unable to assure co-operation from industrial emitters, ii) constrained innovation of control strategies due to defined emission control methods, iii) an inadequate enforcement- and penalty system due to the use of guidelines instead of regulatory standards *(Naiker et al., 2012)*.

There were significant changes in policy and legislation after the onset of democracy in the country. The first of which was the Constitution of the Republic of South Africa. It paved the way for the future development of environmental law within the country. This was mainly due to the environmental clause included in section 24 of the Bill of Rights chapter of the constitutions. It states the following:

"Everyone has the right –

(a) to an environment that is not harmful to their health and well-being; and

(b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that –

(i) prevent pollution and ecological degradation;

(ii) promote conservation; and

(iii) secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development." *(South Africa, 1996)*

The National Environmental Management Act no. 107 of 1998 (NEMA) followed, which strived for the joint governance of the environment by developing adequate decision-making principles *(South Africa, 1998b)*. A policy that too had significant influence during this time was the Energy Policy as the energy sector impacts extensively on the environment and human health. Thus, one of the five (5) objectives included was aimed at managing and reducing the potential health and environmental impacts caused by energy-related activities. This objective targeted the use of solid fuels in residential communities, emission from the energy sector, as well as the sustainable use of fossil fuel resources *(Department of Minerals and Energy, 1998)*.

Subsequent to the above was the White Paper on Integrated Pollution and Waste Management for South Africa (IPWM), which emphasised the use of integrated environmental management strategies to minimise the total pollution and waste burden *(South Africa, 2000)*.

A major shift in the management of air quality in South Africa occurred with the promulgation of the National Environmental Management Air Quality Act no. 39 of 2004 (NEMAQA). It was developed to improve the laws used to regulate air quality with the purpose of protecting human health and the environment. NEMAQA implements three approaches to manage air quality, namely, i) air quality management plans (AQMP), ii) atmospheric emissions licenses (AEL), and national ambient air quality standards (NAAQS) *(South Africa, 2014i)*.

South Africa has declared three regions as ambient air quality priority areas in term of Section 18 (1) of NEMAQA. An area may be declared as a priority area if it is believed that there are specific activities which cause the ambient air quality to exceed the NAAQS and that it may necessitate a targeted management plan to resolve. The first area, declared on 21 April 2006, was the Vaal Triangle Air Shed Priority Area (VTAPA) *(South Africa, 2006)*, followed by the Highveld Priority Area (HPA) declaration on 23 November 2007 *(South Africa, 2007b)*. It was only on 15 June 2012 that the third, namely the Waterberg-Bonjala Priority Area (WBPA) *(South Africa, 2012b)*, was declared a priority as it may in the future exceed the national ambient air quality standard *(Naiker et al., 2012)*.

A recent addition to the process of managing ambient air quality is the Air Quality Offset (NEMAAQO) guidelines published on 18 March 2016 in terms of Section 24 J(a) of NEMA. The NEMAAQO guideline

defines an offset as *"an intervention, specifically implemented to counterbalance the adverse and residual environmental impact of atmospheric emission in order to deliver a net ambient air quality benefit within, but not limited to, the affected airshed where ambient air quality standards are being or have the potential to be exceeded and whereby opportunities and need for offsetting exist" (South Africa, 2016c:13).* It is expected that offsets could provide measures to counteract, within reasonable boundaries, the negative health- and environmental impacts associated with air pollution. However, it is hoped that offsets will be implemented in such a way as to promote improvements that are not environmentally damaging, that contribute to social development, as well as to be economically justifiable. It is important to note that offsets are not meant to be a substitute for regulatory tools, but rather be an auxiliary tool that can be implemented to achieve long-term goals for environmental protection (South Africa, 2016c).

Due to the increasing evidence of air pollution problems in densely populated low-income settlements the DEA, on 24 June 2016, released the Draft Strategy to address Air Pollution in Dense Low-income Settlements (South Africa, 2016d). The strategy was reviewed and published on 17 May 2019 and is now an official policy *(South Africa, 2019)*. Sources of air pollution within these communities include, but are not limited to, un-surfaced roads, biomass- and waste burning, vehicle emissions, tire and cable burning for metal recovery, combustion for heating and cooking, non-fuel burning indoor activities and neighbouring sources such as industry. The strategy aims to ensure that there are coordinated efforts to address air pollution problems in these settlements by facilitating the implementation of various interventions, as well as continued monitoring- and reporting activities to evaluate and improve existing and developing interventions.

1.2.3.2.1. Guidelines and standards for particulate matter in ambient- and indoor environments

It is essential to distinguish between guidelines and standards. A guideline is *"a set of recommended levels against which to compare air quality from one region to another over time"*, while standards refer to *"a set of laws or regulations that limit allowable emissions (...) of air quality beyond a certain limit" (Yassi, 2001)*. Air quality guidelines (AQG) are developed, based on the professional evaluation of current scientific knowledge, to provide guidance on what level of air pollution is acceptable within a certain environment. The main purpose of these guidelines is to make available a standardised manner in which to reduce adverse health impacts associated with varying gaseous and particulate air pollutants *(World Health Organization, 2006a, 2010)*.

Countries which regulate air quality define standards at an annual average, a 24-hour average or both. The most commonly regulated size fractions for suspended particulate matter are $PM_{2.5}$, PM_{10}, and total suspended particles (TSP). The ambient environment is ordinarily regulated to a higher degree than the indoor environment. This is because historically, the focus has been placed on air pollution in the ambient

environment. However, progress is being made towards regulating indoor air pollution, as recent studies have focused more on the interaction between health impacts and the indoor environment.

Joss et al. *(2017)* conducted an in-depth study on the standard levels of ambient pollutants, used by 194 countries. Twenty-four (24) counties had no available data, 53 countries had not defined any standards, while 117 counties had defined a standard and averaging time for at least one pollutant. They found that the standards set by individual countries varied greatly and that these standards comply poorly with the guidelines set by the World Health Organisation (WHO). With regard to particulate matter there are 39- and 101-counties, respectively, that have 24-hour $PM_{2.5}$ and PM_{10} standards, while 62- and 83-countries have annual standards for $PM_{2.5}$ *(Figure 1.3.a)* and PM_{10} *(Figure 1.3.b)* *(Joss et al., 2017)*.

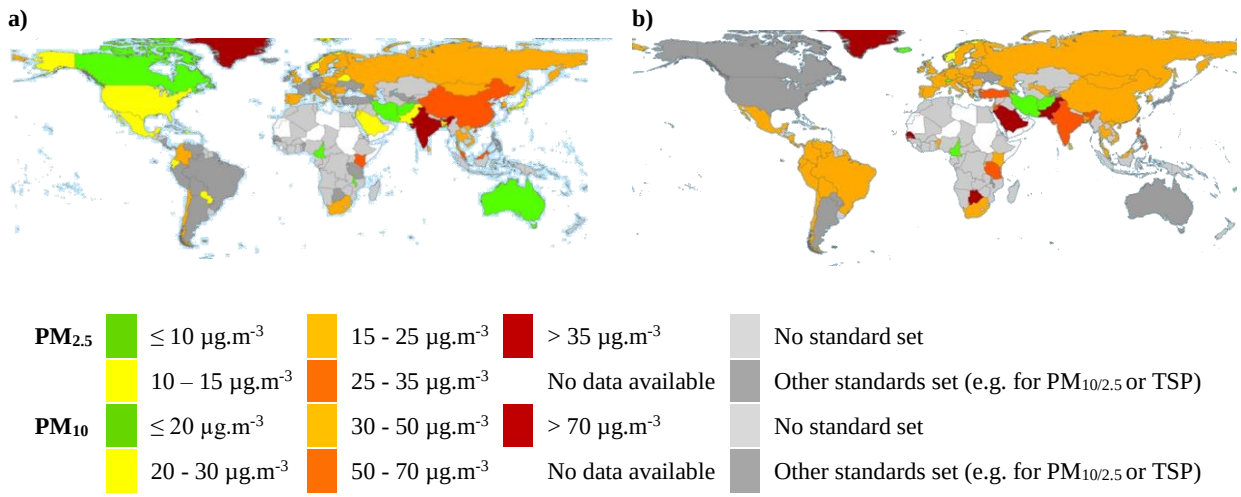


Figure 1.3 Global view of annual average air quality standards for a) $PM_{2.5}$, and b) PM_{10} *(Joss et al., 2017)*.

South Africa has set ambient air quality standards for both 24-hr and annually-averaged $PM_{2.5}$ and PM_{10} *(Table 1.9)*. In 2015 the 24-hr and annual averaging periods of the PM_{10} standard limits were lowered from 120 µg.m^{-3} and 50 µg.m^{-3} to 75 µg.m^{-3} and 40 µg.m^{-3}, respectively. In the following year (2016) the $PM_{2.5}$ standard limits were lowered from 65 µg.m^{-3} and 25 µg.m^{-3} to 40 µg.m^{-3} and 20 µg.m^{-3}, respectively. The lowering of the standard limits was a significant improvement on the previous limits, however, the standards are still higher than the guidelines set by the WHO. The NAAQS allows for four (4) exceedances, at a specific monitoring location, of the 24-hour averaged suspended particulate matter on an annual basis, while zero exceedances are allowed for the annually-averaged suspended particulate matter standard.

Due to the increasing interest in the concept of 'indoor health', the WHO has been contributing more resources to developing a series of guidelines applicable to the indoor environment. Thus far there are three indoor air quality guideline (IAQG) volumes related to i) dampness and mould *(World Health Organization, 2009)*, ii) selected pollutants *(World Health Organization, 2010)*, and iii) household fuel combustion *(World Health Organization, 2014)*. These guidelines are reviewed and developed based on a number of aspects, which include, i) an in-depth evaluation of the indoor sources; ii) the current level of

concentration in the indoor environment; iii) the relationship between indoor and outdoor concentrations; and iv) the existing evidence on health effects in relation to kinetics and metabolism *(World Health Organization, 2006b)*.

Table 1.9 NAAQS for PM_{10} and $PM_{2.5}$ (24-hr and annual), compared to the guidelines set by the WHO (South Africa, 2009c, 2012c, World Health Organization, 2006a, 2010).

	PM_{10} ($\mu g.m^{-3}$)			**$PM_{2.5}$ ($\mu g.m^{-3}$)**		
	24-hour	**Annual**	**Year**	**24-hour**	**Annual**	**Year**
World Health Organisation	50	20		25	10	
Interim target 3	75	30		37.5	15	
Interim target 2	100	50		50	25	
Interim target 1	150	70		75	35	
South Africa	120*	50*	2009	65**	25**	2012
	75*	40*	2015	40**	20**	2016
	-	-	-	25**	15**	2030
Reference method *EN12341 and **EN14907						

The IAQG for particulate matter is exactly the same as defined for the ambient environment, see *Table 1.9 (World Health Organization, 2006b)*. Thus, the 24-hr average guidelines are 25 $\mu g.m^{-3}$ and 50 $\mu g.m^{-3}$ for $PM_{2.5}$ and PM_{10}, respectively. However, some experts recommend that the concentration of indoor air pollutants should be maintained at levels less than or equal to 50% of the current ambient air quality standards *(Bernstein et al., 2008)*, meaning the 24-hr average guidelines should be 12.5 $\mu g.m^{-3}$ and 25 $\mu g.m^{-3}$ for $PM_{2.5}$ and PM_{10}, respectively.

South Africa currently has no set guidelines or standards associated with the particulate matter within the indoor environment, however, the South African National Department of Health (NDoH) identified the need for developing a guideline for the monitoring of domestic indoor air quality *(Department of Health, 2017)*. The main purpose of the guideline is to aid Environmental Health Practitioners (EHP) in assessing indoor air quality in domestic environments to promote their mandate of the protection of health. The guideline has set limit values for various pollutants, however, the most significant pollutants are carbon monoxide and particulate matter. The limit values suggested for indoor PM_{10} is as prescribed by the current NAAQS, thus the 24-hr limit is set at 75 $\mu g.m^{-3}$ and the annual at 40 $\mu g.m^{-3}$. It is important to note that the guideline only refers to PM_{10} with no reference made to limits for $PM_{2.5}$.

The absence of set limits for $PM_{2.5}$ is worrying as the fine fraction particulate matter poses significant health impacts, as previously discussed. The monitoring of indoor air quality in South Africa is underpinned by legislation such as the Health Professions Act (Act No. 56 of 1974), National Building Regulations and Building Standards (Act 103 of 1977), National Health Act (Act No. 61 of 2003), National Environmental Management: Air Quality Act (Act No. 39 of 2004), and Tobacco Products Control Amendment Act (Act

63 of 2008). It is important to note that the indoor air quality guidelines mentioned above are still under review and have not yet come into effect. South Africa has made continual improvements in its ambient air quality management strategies. There are, however, major improvements needed in its approach to indoor air quality management.

1.2.4. Synoptic scale circulation over South Africa

Synoptic-scale circulations impact the manner in which air pollutants are dispersed and transported. Synoptic conditions resulting in high rainfall contributes to the deposition of air pollutants, thus reducing the ambient aerosol pollution concentrations. Circulation causing high wind conditions lend to the improved dispersion of pollutants from one region to another, however, the opposite is true for those associated with weaker winds as the pollutant tend to concentrate in a specific region for longer.

Southern Africa is situated in the subtropical region of the Southern Hemisphere and as such is influenced by circulation patterns that occur in both the temperate latitudes to the south and tropics to the north. The general circulation in the southern hemisphere is dominated by semi-permanent subtropical high-pressure systems which strongly influence the circulation over southern Africa *(Tyson & Preston-Whyte, 2004)*.

The circulation is classified into three categories (fine-, tropical-, and temperate disturbances) as described in *Section 2.4.4.1*. The sub-categories included continental anticyclones, coastal lows and berg winds, easterly waves and -lows, westerly waves, cut-off lows, southerly meridional flow, ridging anticyclones, west-coast troughs, and cold snaps. These patterns are schematically presented below *(Figure 1.4.a- j)*. The monthly occurrence of the five most influential circulation patterns, between 1988 and 1992, is given in *Figure 1.4.k*. The most dominant synoptic-scale circulations influencing the dispersion climatology of the southern African region are continental anticyclones, easterly waves, westerly waves, cut-off lows, and ridging anticyclones. The characteristics and relative importance of the dominantly observed synoptic circulation patterns are discussed in more detail below in *Section 5.1.1*.

1.2.4.1. Fine-weather and mildly disturbed conditions

1.2.4.1.1. Continental anticyclones

Continental anticyclones *(Figure 1.4.a)* are associated with the divergence of wind-fields near the surface and convergence of air masses in the upper troposphere resulting in large scale subsidence which causes air to move vertically down. Convective mixing of the atmosphere is inhibited by adiabatic heating bringing about a highly stable atmosphere resulting in inversion layers. The inversions form at ~850 hPa over the escarpment and at ~ 300 hPa, ~500 hPa, and ~700 hPa over the plateau regions *(Tyson & Preston-Whyte, 2004)*. This pressure system dominates the southern Africa region throughout the year *(Figure 1.4.k)* with

the highest occurrences present in mid-autumn to late-winter (range: ~55% to ~70%) and the lowest during mid-spring to late-summer (range: ~15 to ~20%).

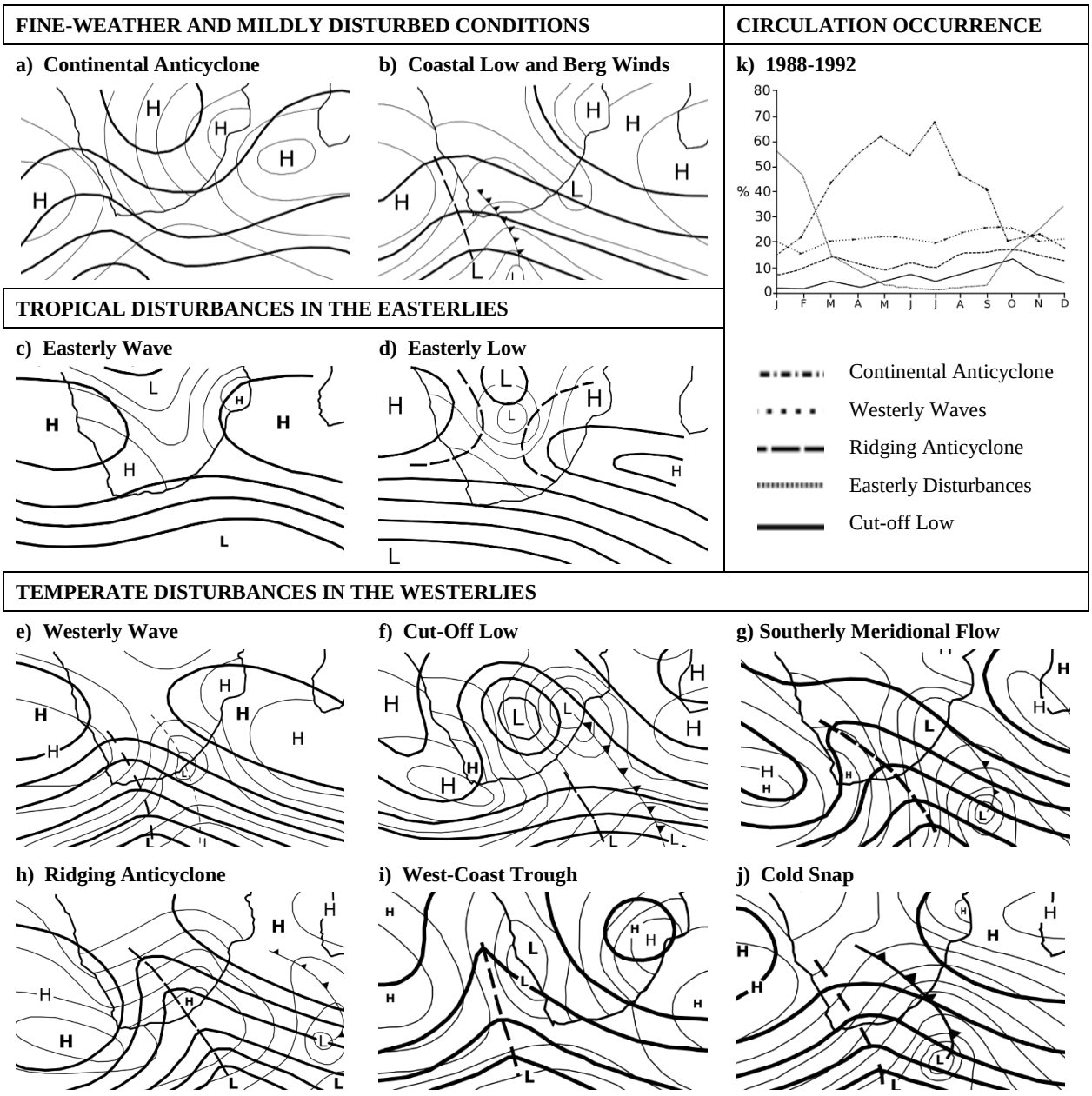


Figure 1.4 A schematic classification of southern African weather types based on the dominant circulation patterns at the surface (light lines) and 500hPa (heavy lines): fine weather (a-b); tropical disturbances (c-d), temperate disturbances (e-j), and the occurrence of the circulation types between 1988 and 1992 (k) *(Tyson et al., 1996; Tyson & Preston-Whyte, 2004).*

1.2.4.2. Tropical disturbances in the easterlies

1.2.4.2.1. Easterly waves

Easterly wave disturbances *(Figure 1.4.c)* affecting South Africa are typically associated with warm humid winds occurring between the Inter-Tropical Convergence Zone (ITCZ) and the subtropical high-pressure belt. These disturbances are barotropic in nature and appear mostly at lower atmospheric levels, between 850 hPa and 700 hPa, as open waves or closed low pressures. The surface trough associated with these waves is characterised by a well-defined boundary. This boundary divides the dry air in the south-west from the moist air in the north-east. This circulation pattern is also associated with the formation of precipitation due to strong low-level convergence taking place to the west of the trough and divergence within the atmosphere above 500 hPa *(Tyson & Preston-Whyte, 2004)*. The pressure system occurs most frequently during summer (30-55%) months *(Figure 1.4.k)* and less so during winter (<10%) periods. This is mainly due to the northward migration of the pressure system during the winter.

1.2.4.3. Temperate disturbances in the westerlies

1.2.4.3.1. Ridging anticyclones

Ridging anticyclones *(Figure 1.4.h)* are associated with westerly waves (discussed below) as it forms when a South Atlantic anticyclone edges in behind the preceding westerly wave disturbance. The pressure system is associated with widespread precipitation over the eastern parts of the country brought about by the advection of moist unstable air over the eastern interior *(Tyson & Preston-Whyte, 2004)*. The averaged frequency of ridging anticyclones *(Figure 1.4.k)*, between 1988 and 1992, indicated three peak periods of occurrence in early-autumn (~5%), early-winter (~10%), and mid-spring (~15%).

1.2.4.3.2. Westerly waves

Westerly wave disturbances *(Figure 1.4.i)* are baroclinic Rossby waves associated with low-pressure systems. Similarly to the easterly waves, convergence occurs to the west behind the trough resulting in the unstable conditions forming clouds and precipitations. However, stable conditions prevail to the east ahead of the trough due to slowly diverging air masses *(Tyson & Preston-Whyte, 2004)*. The pressure system occurs most frequently from mid-spring to mid-autumn (~15% to 25%) and less seldom during late-autumn to early-spring (~20 to 24%). There is a lower variability in seasonal occurrence compared to the continental anticyclone and easterly waves circulations *(Figure 1.4.k)*.

1.2.4.3.3. Cut-off lows

Cut-off low-pressure depressions *(Figure 1.4.f)* are an exacerbated form of the westerly wave temperate disturbance. The closed circulation forms as a result of a trough extending down toward the surface and

then being displaced north in the direction of the equator. These systems are unstable baroclinic low pressures associated with strong convergence and vertical movement of air. These depressions often result in heavy rainfall that often contributes to flooding *(Tyson & Preston-Whyte, 2004)*. Historically *(Figure 1.4.k)*, cut-off lows appear to have a semi-annual variation with peaks occurring in early-autumn to early-winter (~5% to ~10%) and during spring periods (~8% to 13%). The lowest frequencies tend to occur during the summer months (<5%).

1.3. Problem statement

Three specific areas of interest, related to indoor air pollution in developing countries, were identified as requiring further research attention. These included i) epidemiology, ii) exposure assessment, and iii) intervention-based studies. There are two definite shortfalls in indoor air quality exposure studies in South Africa, namely:

(a) studies that characterise indoor pollutants are few and tend to have a very narrow geographic focus;
(b) to the knowledge of the author, there are no published source apportionment studies that identify sources contributing to indoor air pollution specifically.

These shortfalls impede the understanding of residential indoor air pollution, the impacts it may have, and the possible mitigation and management strategies in South Africa. The purpose of this study is thus to investigate the indoor particulate matter on a larger geographical scale with a focus on low-income residential settlements in South Africa.

1.4. Research aim and objectives

Considering the research problems identified in the above literature review, the overall aim of this research project is to evaluate the state of respirable particulate matter (PM_4) within the indoor environment of low-income residential settlements in South Africa across various spatial and temporal resolutions. In particular, the main objectives and specific sub-objectives of this study are to:

Objective I – evaluate the use of photometric particulate matter monitors within the indoor environment of low-income residential settlements in South Africa, by:

(a) estimating photometric calibration factors for respirable particulate matter (PM_4) in various indoor micro-environments across individual settlements and sampling campaigns;
(b) investigating the difference in PM4 mass concentrations measured between collocated DustTrak Model 8520, DustTrak II Model 8530, and SidePak AM510 photometric instruments; and

(c) investigating the difference in particulate mass concentrations of varying size fractions (PM_1, $PM_{2.5}$, PM_4, and PM_{10}) for collocated photometric instruments.

Objective II – assess the status of indoor air quality with respect to the mass concentrations of PM_4 measured in the indoor environment of low-income residential settlements in South Africa, by:

(a) investigating the spatial and temporal variability of the continuous PM_4 mass concentration;
(b) estimating the exceedences of the 24-hr $PM_{2.5}$ NAAQS and WHO guidelines.

Objective III – characterise sources associated with PM_4 trace elements measured in the indoor environment of low-income residential settlements in South Africa, by:

(a) investigating the spatial and temporal variability of the gravimetric PM_4 mass concentrations;
(b) investigating the spatial and temporal variability of the PM_4 trace element mass concentrations;
(c) estimating the enrichment of elements relative to crustal soil;
(d) identifying possible sources related to the trace elements;
(e) estimating the relative contribution of potential sources to the indoor PM_4 mass concentration;

Objective IV – investigate the influence of synoptics on local meteorology and its associated impact on particulate pollution in the indoor environment of low-income residential settlements in South Africa, by;

(a) characterising the regional synoptics and local meteorological condition observed during the study period;
(b) investigating the possible impact of the observed meteorological conditions on the indoor PM_4 mass concentrations.

1.5. Significance of the study

Findings obtained from this study could contribute to current scientific knowledge by:

(i) improving our understanding of the use of photometric particulate instruments;
(ii) improving our understanding of indoor particulate pollution in the low-income residential settlements in South Africa;
(iii) raising the awareness of residents concerning the air that they breathe;
(iv) informing future health-impact studies;
(v) aiding in the identification of possible focus areas for mitigation or interventions to reduce particulate pollution; and
(vi) informing the development of guidelines, policies and standards for residential indoor environments.

1.6. Scope and limitations

This study will focus on developing a better understanding of indoor particulate pollution in South Africa by evaluating respirable particulate matter within the indoor environment of low-income residential settlements in South Africa. The settlements selected for monitoring are situated in one of two regions, namely the Highveld and Lowveld. These two regions were selected due to the contrasting differences in their geographical location, demographics, fuel use and climatic conditions. Settlements outside of these regions were not included in the study. The limitations of the study include the following:

- only a single particle size fraction was monitored (excluded gases);
- only elemental species were analysed (excluded ionic and carbon analysis);
- not all houses were sampled over the same period due to instrument constraints; and
- local rainfall data from the SAWS ambient monitoring stations were incomplete and thus the link between this variable and PM4 could not be investigated.

1.7. Structure of the thesis

This thesis comprises of the following six (6) chapters as outlined below:

Chapter 1 – Overview: provides the background and justification for the study, including a detailed literature review exploring the state and knowledge surrounding particulate aerosols, indoor air quality aspects, health impacts, and air quality management guidelines and legislation. Lastly, the research aim, objectives, scope, limitations and thesis structure are also outlined.

Chapter 2 – Data acquisition and analysis methodology: introduces the study area and contains a detailed description of the data acquisition and analysis methodologies used. It includes the sampling procedures, sample analysis techniques and analytical procedures implemented for data interpretation. The data collected for this study is an amalgamation of four different research projects, thus emphasis is placed on providing sufficient detail surrounding the specific sampling sites and the approach taken at each. Furthermore, the ethical considerations, assumptions and limitations surrounding the study are elaborated upon.

Chapter 3 – Field evaluation of photometric instruments (Objective I): evaluates the use of photometric light scattering instrumentation within the indoor environment of residential homes. This includes investigating the variations in calibration factors within the microenvironment of individual households across settlements. In addition to the above mentioned two collocated case studies are also explored, the first of which looks at the inter-comparison of photometric instruments fitted with the same respirable

particulate inlet, and secondly instruments that are fitted with inlets of varying size fractions (PM_1, $PM_{2.5}$, PM_4, and PM_{10}).

Chapter 4 – Characterisation and source identification of respirable indoor particulate matter (Objectives II & III): characterises PM_4 within the residential indoor environment focusing on particulate mass concentration and associated trace elements. This is achieved by investigating the various diurnal and seasonal patterns and household variability by exploring extreme events. Possible sources contributing to particulate aerosols are also identified.

Chapter 5 – Meteorology of the study area: investigates the synoptic- and local meteorological conditions for each measurement campaign and its possible impacts on indoor PM_4.

Chapter 6 – Summary and conclusions: summarises the main findings associated with each objective as set out in Chapter 1 and presents the conclusions to the study as a whole.

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The background and justification of the research are given, including a detailed literature review of the knowledge surrounding indoor air quality in South Africa. The aims, research objectives, scope and limitations were outlined within the context of the research. The following chapter discusses in detail the study design and associated data acquisition and analysis methodologies used to reach the aim and specific objectives.

CHAPTER 2: DATA ACQUISITION AND ANALYSIS METHODOLOGY

The purpose of this chapter is to outline the research design. This includes a detailed description of the study area, experimental procedures, and statistical analysis methods implemented in the study. Emphasis is placed on providing sufficient detail surrounding the specific sampling sites and the methodological approach taken at each. Furthermore, the ethical considerations surrounding the study are elaborated upon.

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2.1. Research design

A *"quantitative dominant mixed methods"* approach, described by *Johnson, Onwuegbuzie, and Turner (2007:124)* as including primarily quantitative- and less extensively qualitative methods, was adopted in this research. The conceptual flow-diagram *(Figure 2.1)* outlines the approach taken.

The quantitative research methods included three (3) experimental procedures, namely, i) continuous monitoring; ii) intermittent filter sampling, and iii) collocated monitoring techniques. The data obtained from the above-mentioned methods constitute the primary data for this study. These methods are discussed in detail in *Sections 2.3.2.1, 0* and *0* respectively. In addition, secondary quantitative data included the national census data from Statistics South Africa (SSA) along with climate and meteorological data from the South African Weather Service (SAWS). These are discussed in detail in *Sections 2.3.2.5.1* and *2.3.2.5.2*. The qualitative research method used questionnaire interviews conducted at the household level. The survey data are secondary data and used to contextualise the quantitative data *(see Section 2.3.2.5.3)*. The mixed-method approach allows comprehensive and integrated assessment of the stated objectives *(Dunning et al., 2008; Johnson & Onwuegbuzie, 2004)*.

This study is an amalgamation of four different research projects which included the following; i) the Quality of Life Baseline Survey in Selected Communities surrounding Sasol-Secunda (Sasol Offset Pilot Study); ii) the Household Emissions Offset Study in the Highveld Priority Area (Eskom Offset Pilot Study); iii) the Prospective Household observational cohort study of Influenza, Respiratory Syncytial virus and other respiratory pathogens community burden and Transmission dynamics in South Africa Study (PHIRST); and iv) the infection Diseases Early-Warning System (iDEWS) project.

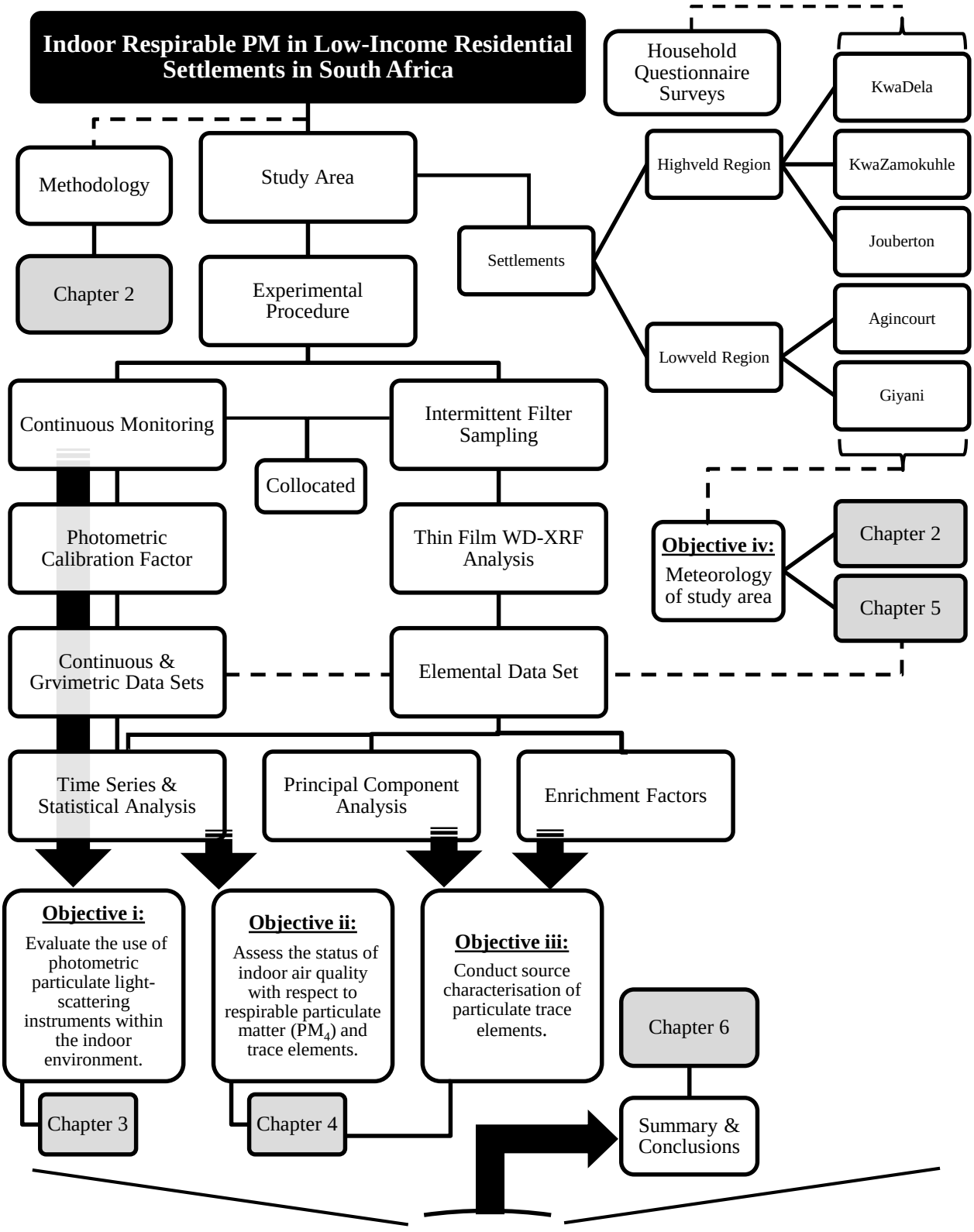


Figure 2.1. Conceptual flow diagram outlining the research design taken for evaluating respirable indoor particulate matter in low-income residential settlements in South Africa.

The two offset studies were similar in nature. They were both aimed at identifying possible interventions that could be implemented at the household level to reduce ambient and indoor particulate emissions within these communities. The primary objective of the PHIRST project was to estimate the community burden of influenza and RSV and assess its associated transmission dynamics. The impact of housing and environmental factors such as air quality was among the secondary objectives. Lastly, the iDEWS project was aimed at investigating the prevalence of infectious diseases (diarrhoeal disease, lower respiratory infection, and malaria) at a household level with the purpose of establishing an early warning system. Similarly to the PHIRST project, environmental aspects (water- and air quality) were identified as an area of concern and investigated as secondary objectives. The aims and objectives of the above-mentioned projects impacted on the household selection and measurement strategies used at each sampled settlement. The specific strategies applied at the individual sites are further discussed in detail.

2.2. Study area characterisation

South Africa covers the latitudinal-longitudinal area of 22° - 35°S and 15° - 35°E and has specific topographic features which influence the weather and climate of the region and subsequently affects the way in which pollutants are dispersed within the atmosphere *(Scheifinger & Held, 1997)*. The study area covers the north-eastern quadrant of South Africa including the Highveld- and Lowveld) regions *(Figure 2.2)*. These regions include the North-West-, Gauteng-, Free-State-, Limpopo-, and Mpumalanga provinces.

The Highveld region of South Africa forms part of the inland plateau, a segment (~163 615 km^2) of the great escarpment of the southern African subcontinent. It is characterised by average altitudes ranging between ~1400 to 1700 meters above mean sea level (m.a.m.s.l.). Due to the underlying geology, the majority of coal mines in South Africa are found within this region. It is considered to be the industrial epicentre of the country as it houses most of the high-capacity coal-fired power plants. Anthropogenic emission sources include mining activities, petrochemical industries, biomass burning (controlled and uncontrolled), as well as residential combustion activities for the purpose of cooking and space heating *(Korhonen et al., 2014)*. Three (3) of the selected settlements, namely KwaDela (-26.463885°S; 29.665851°E), KwaZamokuhle (-26.133883°S; 29.733906°E), and Jouberton (-26.901252°S; 26.598405°E) are located within this region, two (2) of which are within the Highveld Priority Area *(Figure 2.2)*.

The Lowveld region is a low-lying landscape that extends from the Mozambique coastal plain inland towards the foot slopes of the Drakensberg Great Escarpment and covers an area of ~56 852.5 km^2. The region is characterised by an average altitude of around 700 meters above mean sea level. The remaining two settlements, namely Agincourt (-24.810546°S; 31.253114°E), and Giyani (-23.308208°S; 30.707208°E) are situated within this region *(Figure 2.2)*.

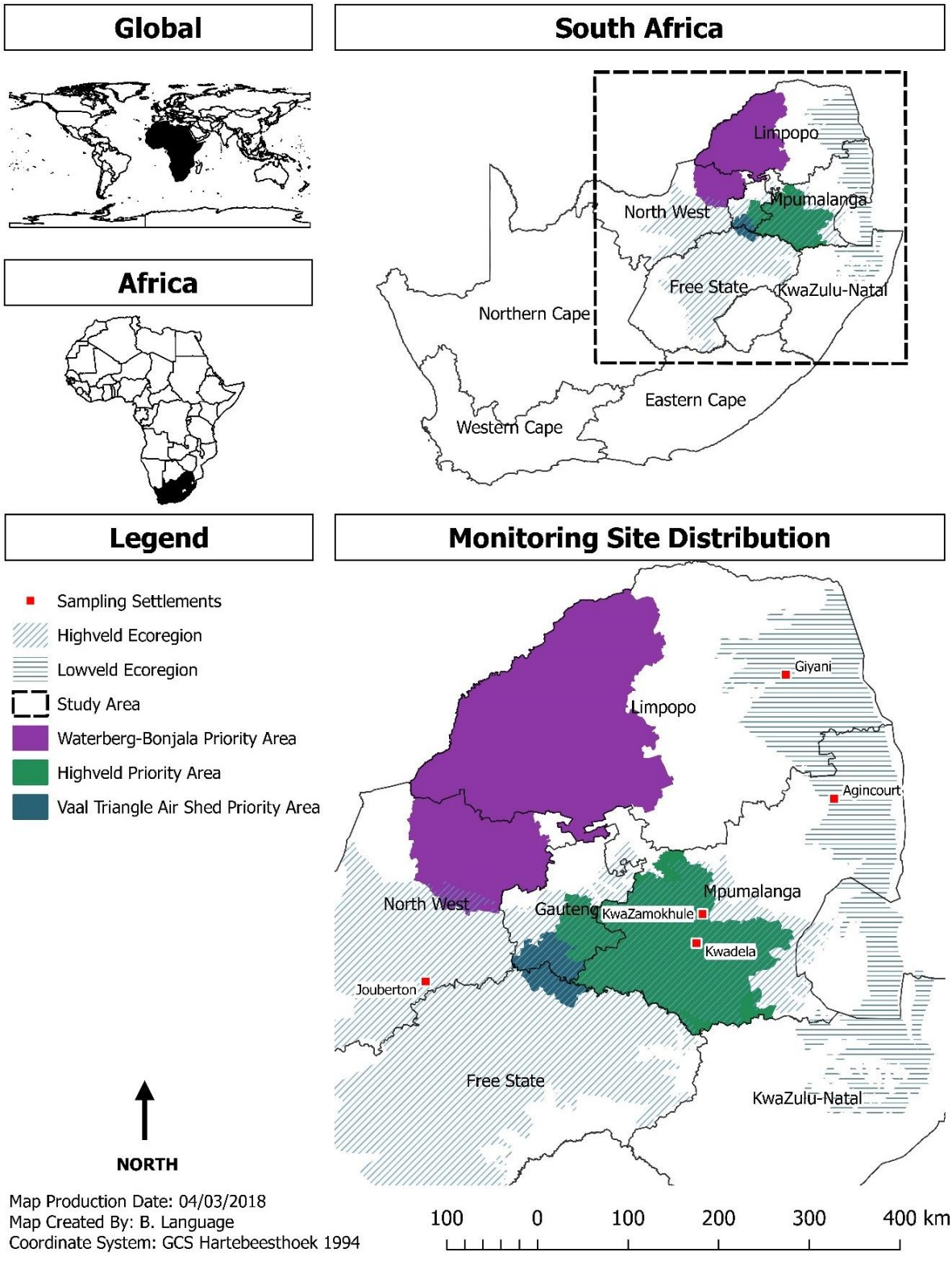


Figure 2.2. Map of South Africa illustrating the geographical location of the study area including the Highveld- (diagonal stripes) and Lowveld Region (horizontal stripes), the Highveld Priority Area (shaded green), Vaal Triangle Air-Shed Priority Area (shaded blue), and the Waterberg-Bonjala Priority Area (shaded purple). The selected sampling settlements (red squares) are also indicated on the map.

2.2.1. Energy use patterns in the study region

A notable difference between the two regions is its energy fuel (electricity, gas, paraffin, wood, coal, and dung) use for cooking and heating activities. At a household level, electricity (70.8%, ±4.9) is the main source of energy used followed by wood (14.0%, ±3.4), paraffin (9.1%, ±0.8), gas (3.2%, ±0.5), coal (1.5%, ±1.1), and dung (0.3%, ±0.04). The main energy options of concern for this study are electricity, wood, and coal. The percentage of households per province utilising the above-mentioned energy sources, for cooking and heating purposes, are summarised in *Figure 2.3 a* and *b*.

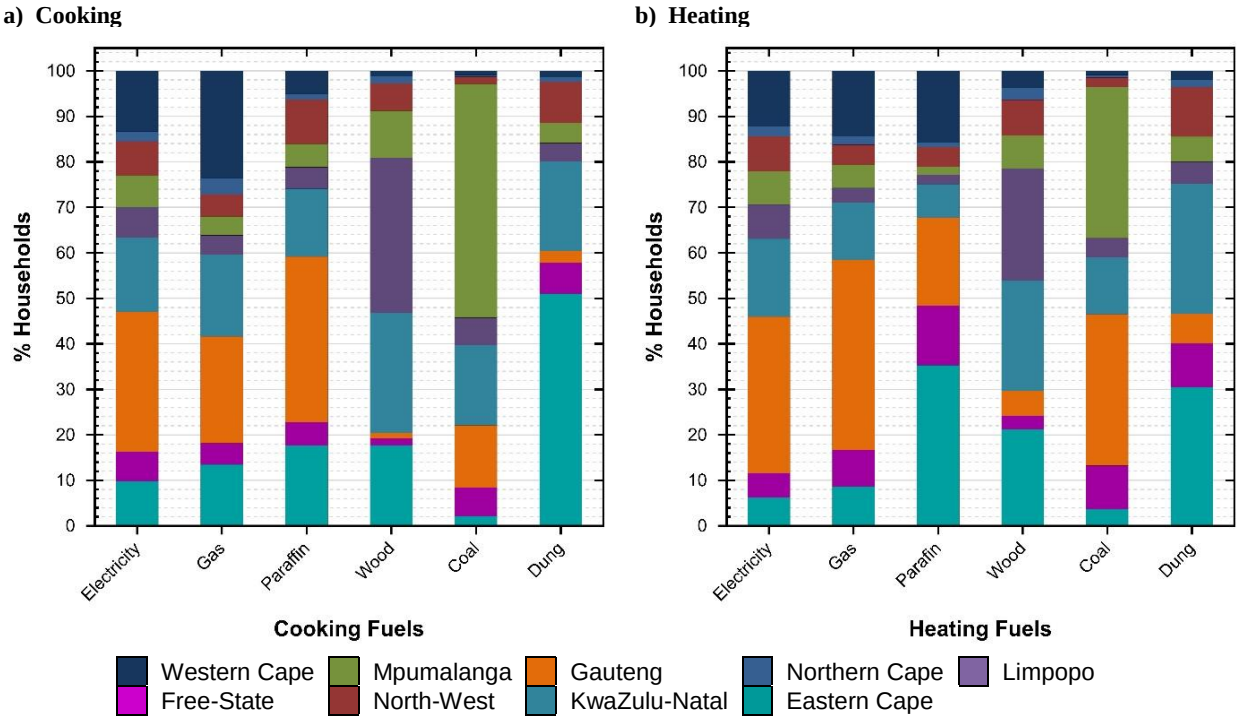


Figure 2.3. Stacked percentages of households (per province) utilising electricity, gas, paraffin, wood, coal, and dung as their primary energy for a) cooking- and b) heating activities in South Africa in 2011 *(Statistics South Africa, 2011)*.

The majority of the households using electricity *(Figure 2.3)* as their main energy are situated in Gauteng (62.5.6%, ±2.6) followed by KwaZulu-Natal (16.7%, ±0.6) and the Western Cape (12.8%, ±0.8). The Eastern-Cape, Free State, Limpopo, Mpumalanga, and North-West provinces each accounted for approximately seven (7) percent of the households. Less than three (3) percent of the households were located in the Northern Cape. Electricity is the primary energy source used for both cooking (74.3%, ±8.4) and heating (67.3%, ±9.7) activities across all nine provinces *(Figure 2.4)*.

Wood using households *(Figure 2.3)* are mainly found in Limpopo (29.4%, ±6.7) followed by KwaZulu-Natal (25.3%, ±1.5) and the Eastern Cape (19.4%, ±2.5). Mpumalanga and North-West provinces accounted for approximately eight (8) percent each. The remaining provinces contributed less than three

(3) percent, respectively. Across the nine provinces, wood is the second most popular energy source used for cooking (12.6%, ±12.3) and heating (17.4%, ±9.4) activities *(Figure 2.4)*.

Most of the households using coal *(Figure 2.3)* as their main energy are situated in Mpumalanga (42.3%, ±12.8) followed by Gauteng (23.5%, ±13.8) and KwaZulu-Natal (15.0%, ±3.6). The Free-State and Limpopo provinces accounted for approximately six (6) percent each. The remaining provinces contributed less than three (3) percent of households, respectively. On average coal is used only by a very small percentage of South African households for cooking (0.7%, ±16.2) and heating (2.3%, ±13.2) activities *(Figure 2.4)*.

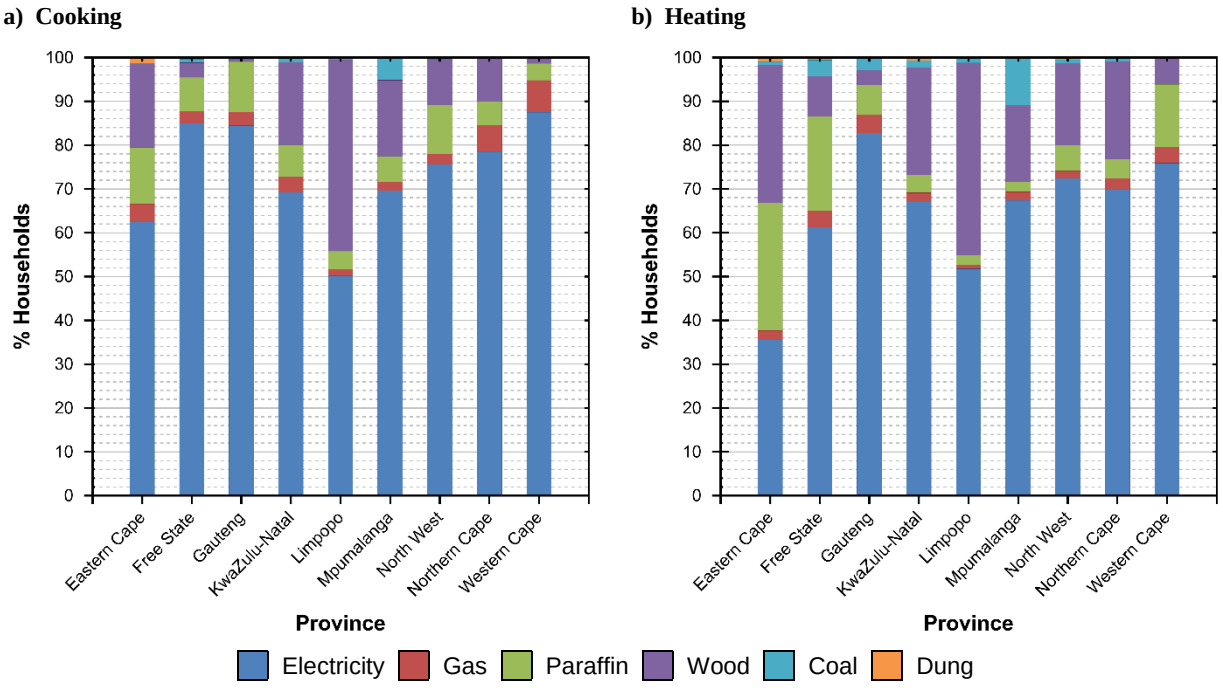


Figure 2.4. Stacked percentages of households utilising electricity, gas, paraffin, wood, coal, and dung as their primary energy for a) cooking- and b) heating activities in South Africa in 2011, categorised by province *(Statistics South Africa, 2011)*.

The differences in household fuel use that exists between the provinces support the rationale for selecting residential communities located within the two identified regions. The five (5) selected settlements (KwaDela, KwaZamokuhle, Jouberton, Agincourt, and Giyani) are discussed with regard to their:

- physical locations (topography);
- land uses;
- socio-economic aspects (population, household income, housing type, household size);
- energy sources used for cooking and heating activities; and
- the climatic conditions (temperature, relative humidity, rainfall).

2.2.2. Settlement characterisation

2.2.2.1. KwaDela

KwaDela (-26.463232°S; 29.664151°E) is a small settlement (~0.45 km^2) positioned to the south of Davel, next to the N17 national roadway between the towns of Ermelo and Bethal. It forms part of the Msukaligwa Local Municipality situated within the larger Gert Sibande district municipality of Mpumalanga. The topography surrounding the settlement (50km^2) *(Figure 2.5.b)* varies between ~1400 and 2000 m.a.m.s.l.

The settlement is far from any major industrial activities and is surrounded mostly by natural grassland vegetation (54.9%) and cultivated agricultural lands (34.9%) *(Figure 2.5.c)*.

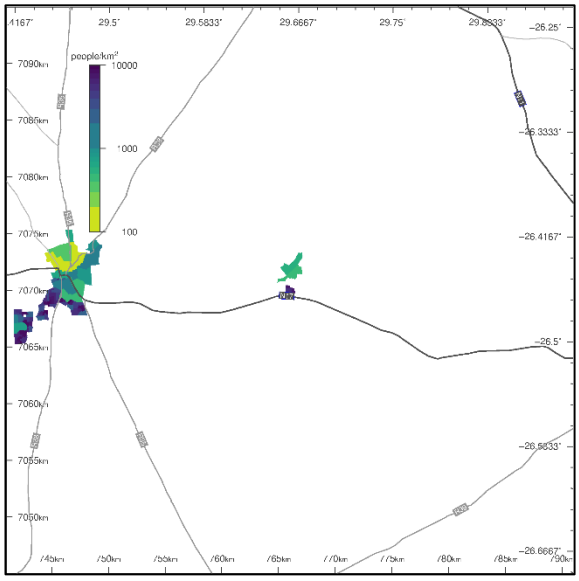
The national census *(Statistics South Africa, 2011)* provides the relative position of the populated areas *(Figure 2.5.a)*. It shows a moderately high population density as the settlement consists of approximately 984 households and ~3 800 people. The majority (~68%) of the population is below 24 years of age. There is a high rate of poverty with ~15% of households having no income and ~65% having a monthly income below R3 200. This indicates that most of the households do not have sufficient income to support their families. There are mostly (>90%) formal brick houses and some (<10%) informal housing types. The average household size ranges between one (1) and five (5) persons with ~22% of households having more than five occupants.

The settlement is electrified and most of the residents have access to electricity, however, ~45% of the households still use coal as a primary energy source for cooking and heating activities.

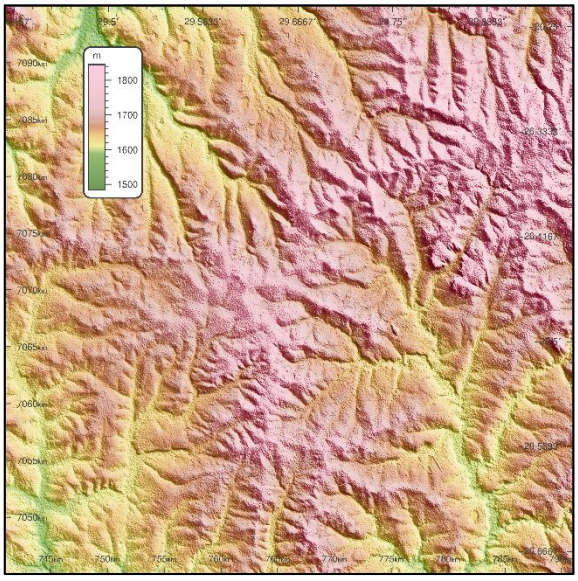
The SAWS Bethal meteorological station (AMS-03) is the nearest long-term monitoring station to KwaDela. The station is situated 1650 m.a.m.s.l. at ~22km west of the settlement. The data obtained from this station covers a 22-year period (1989-2010) and are summarised in *Table B.1.* The region typically has warm to hot summers and cold to warm winters.

The average of the daily mean summer (December-January-February) temperatures range between ~18 and ~20°C while winter (June-July-August) temperatures range between ~9 and 12°C *(Figure 2.6.a)*. During summer the average of the daily maximum temperature ranges from ~25 to 26°C with average daily minimums ranging from ~13 to 15°C. During winter these can reach between ~18 to 21°C and ~ -1 to 3°C, respectively. However, during summer the mean highest maximums range between ~32 and 34°C while the mean lowest minimums range from ~8 to 10°C. Throughout winter these temperatures range from ~26 to 29°C and ~ -4 to -6°C. The lowest minimum recorded during this period was -10.6 °C on 3 July 1992.

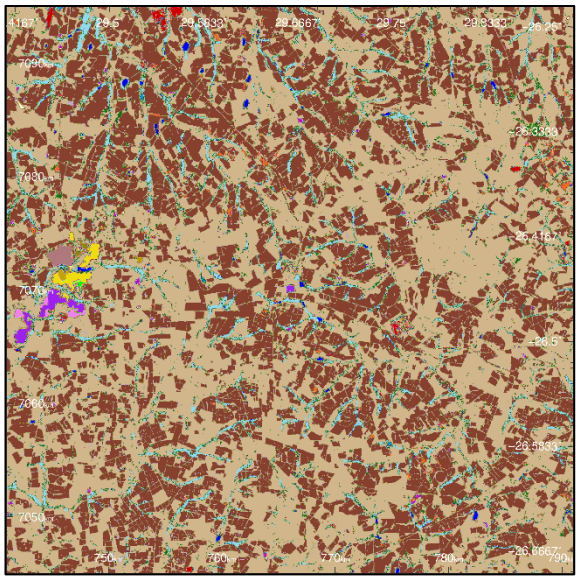
a) Population Density



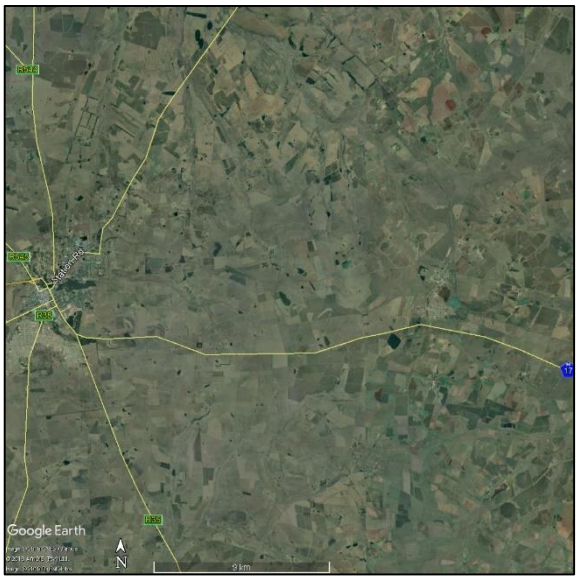
b) Topography



c) Land Cover



d) Aerial Photograph



Legend:

Population Density (people/km²)

100 — 1000 — 10000

Elevation (m)

1500 — 1600 — 1700 — 1800

Land Use

Grassland	54.9%	Cultivated Commercial Field	34.9%	Wetlands	4.2%
Mines	1.9%	Thicket/Dense Bush	0.6%	Woodland/Open Brush	0.6%
Plantations	0.6%	Urban Residential	0.4%	Water Permanent	0.3%
Bare Bone Vegetation	0.3%	Low Scrubland	0.2%	Urban Township	0.2%
Urban Built-up	0.2%	Urban Industrial	0.1%	Indigenous Forest	N/A
Mines Water	6.3 km²	Water Seasonal	4.9 km²	Urban Smallholding	4.9 km²
Urban Commercial	3.8 km²	Urban Informal	3.5 km²	Urban Sports	2.5 km²
Urban Village	2.3 km²	Erosion	1.9 km²	Urban Schools	1.7 km²
Cultivated Orchard	1.3 km²	Mines Buildings	0.8 km²	Cultivated Subsistence	<0.1 km²

Figure 2.5. KwaDela settlement (50km²) represented by a) the population density, b) topography, c) land cover, and d) aerial photograph.

There are approximately 14 and 45 days per year that reach temperatures above 30°C and below 0°C, respectively. The majority of these sub-zero days occur during winter which is also when we expect the residents of the settlements to actively participate in residential heating through solid fuel combustion activities.

The relative humidity is highest during summer months *(Figure 2.6.b)* and the diurnal pattern indicates that the relative humidity is highest during the morning periods and decreases toward mid-afternoon (14h00).

KwaDela falls in the summer rainfall region. The area can get up to ~750 mm of precipitation per year, with a maximum of 1073 mm measured for 2000 and a minimum of 393 mm for 1999. Most of the rainfall occurs from mid-spring to early autumn *(Figure 2.6.c)*.

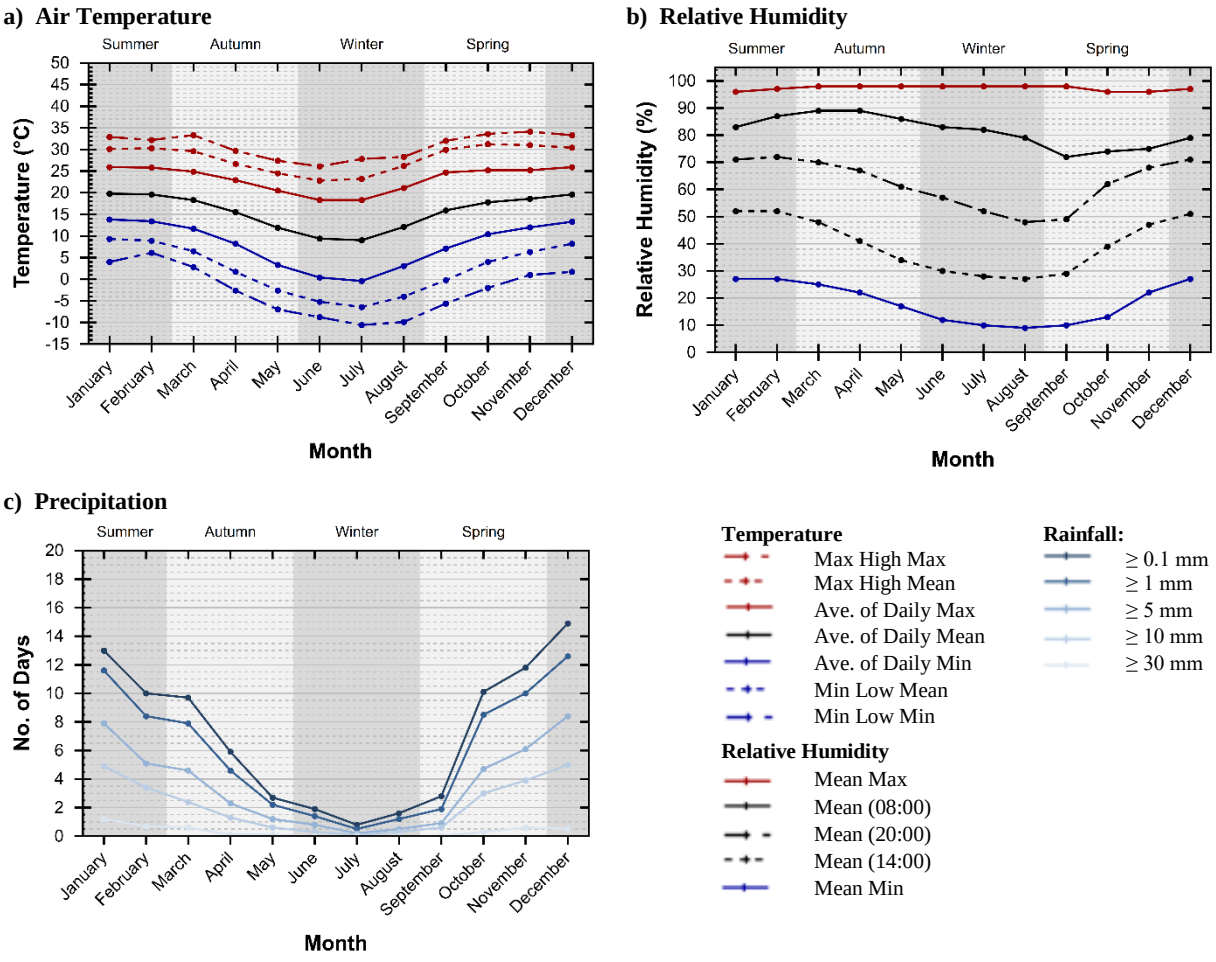


Figure 2.6. The yearly trend in the climatic conditions (1981-2010) for Bethal including a) air temperature, b) relative humidity, and c) precipitation *(South African Weather Service, 2018)*.

2.2.2.2. KwaZamokuhle

KwaZamokuhle (-26.133827°S; 29.733855°E) is positioned to the north-east of Hendrina and can be accessed via the R38. The settlement lies within the Steve Tshwete Local Municipality and is a mere 70km north-east of KwaDela. The topography surrounding the settlement (50km^2) *(Figure 2.8.b)* varies between ~1500 and 2000 m.a.m.s.l.

The settlement is surrounded by grasslands (~51.5%) and cultivated agricultural lands (~33.6%). There is also a water body at the south-eastern edge of the settlement *(Figure 2.8.c)*.

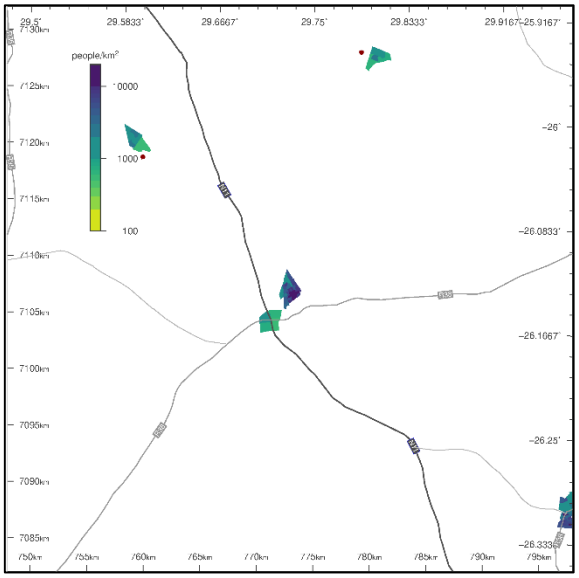
The settlement is much larger than KwaDela. It shows a moderate to high population density *(Figure 2.8.a)* as the settlement consists of approximately 20 500 residents housed in ~5 900 households. The majority (~52%) of the population are below 24 years of age. There is a high rate of poverty with ~14% of households having no income and ~40% of having a monthly income below R3 200. This indicates that more than half of households do not have sufficient income to support their families. However, the range of income levels is more diverse with a small percentage of households receive an above-average income. There are mostly (~82%) formal brick houses and ~15% informal types of housing. The average household size ranges between one and five persons with ~18% of households having more than five occupants.

The settlement is electrified and most of the residents have access (~65%), however, ~30% of the households still use coal *(Figure 2.7)* as a primary energy source for cooking and heating activities.

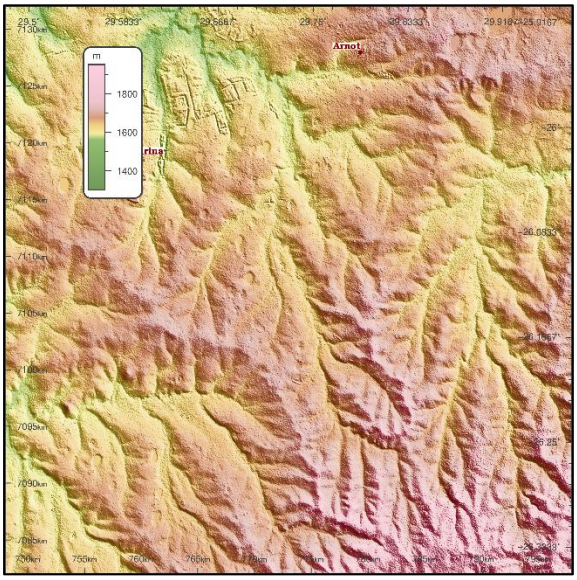
Figure 2.7. Solid fuel burning (coal) in a typical Union No.7 coal stove in KwaZamokuhle during winter (photographs by B. Language 2015).

Similarly to KwaDela, the SAWS Bethal meteorological station (AMS-03) is the nearest long-term monitoring station to KwaZamokuhle. The climatic conditions experienced in KwaZamokuhle was thus the same as that of KwaDela.

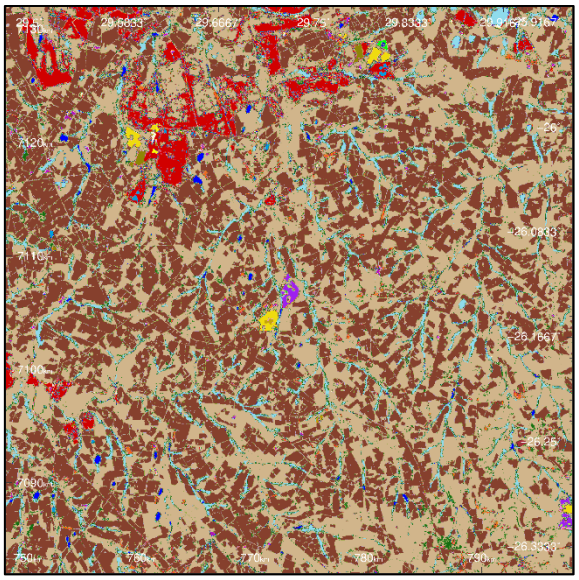
a) Population Density



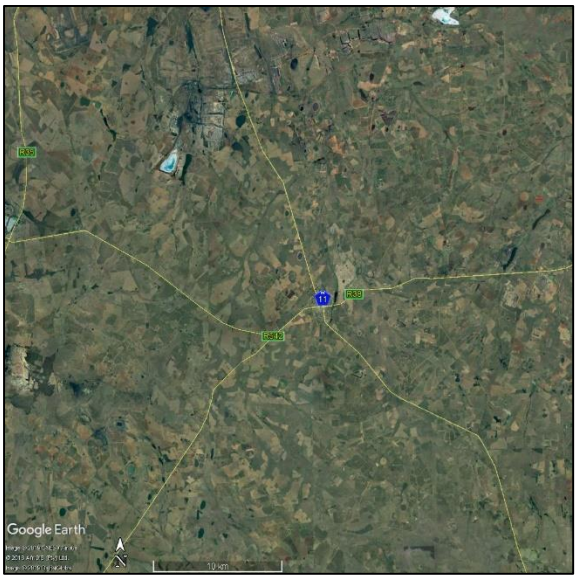
b) Topography



c) Land Cover

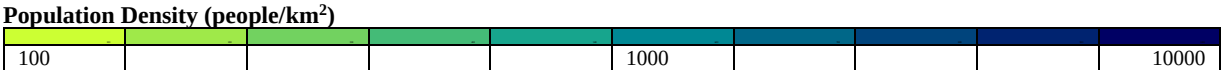


d) Aerial Photograph



Legend:

Population Density (people/km²)



Elevation (m)

Land Use

Grassland	51.5%	Cultivated Commercial Field	33.6%	Wetlands	4.5%
Mines	3.9%	Thicket/Dense Bush	0.9%	Woodland/Open Brush	0.8%
Plantations	1.2%	Urban Residential	0.5%	Water Permanent	0.6%
Bare Bone Vegetation	0.5%	Low Scrubland	0.4%	Urban Township	0.3%
Urban Built-up	0.3%	Urban Industrial	0.2%	Indigenous Forest	N/A
Mines Water	0.1%	Water Seasonal	6.0 km²	Urban Smallholding	0.3%
Urban Commercial	6.8 km²	Urban Informal	5.0 km²	Urban Sports	5.2 km²
Urban Village	2.6 km²	Erosion	2.5 km²	Urban Schools	1.6 km²
Cultivated Orchard	0.9 km²	Mines Buildings	1.4 km²	Cultivated Subsistence	<0.1 km²

Figure 2.8. KwaZamokuhle settlement (50km²) represented by a) the population density, b) topography, c) land cover, and d) aerial photographs.

2.2.2.3. Jouberton

Jouberton (-26.901252°S; 26.598405°E) is located adjacent to the N12 to the west of Klerksdorp in the North-West province. It is situated in the boundaries of the City of Matlosana Local Municipality. The topography surrounding the settlement (50km^2) *(Figure 2.9.b)* varies between ~1000 (towards the south) and 2000 m.a.m.s.l. (towards the north).

The settlement is surrounded by grasslands (46.2%) and cultivated commercial fields (43.7%). The settlement itself is considered to be a largely urbanised low-income community in close proximity to larger urban industrial activities (15.9km^2) within the Klerksdorp region *(Figure 2.9.c)*.

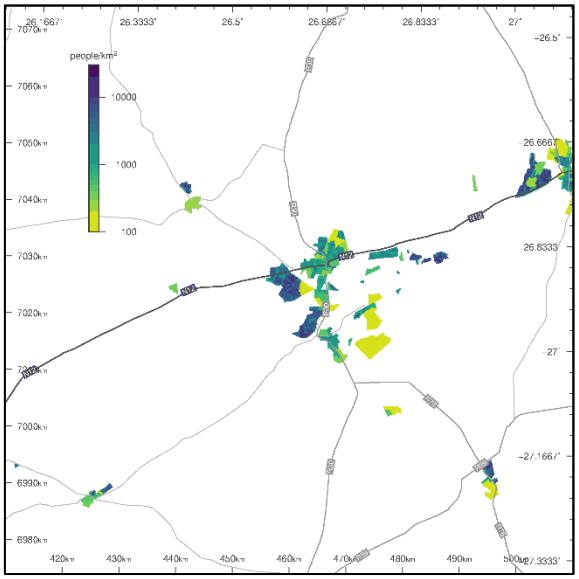
The settlement is the largest in this study with a high population density *(Figure 2.9.a)*. There are ~114 000 people housed in ~33 000 households. The majority (~50%) of the population are below 24 years of age with ~35% being between the ages of 25 and 54 years. There is a high rate of poverty with ~16% of households having no income and ~58% of having a monthly income below R3 200. Most of the houses are formal brick (~72%) houses, however, ~22% of the structures in the community are considered informal. The average household size ranges between one and three persons with ~42% of households having more than three occupants.

The settlement is electrified, however, ~12% and ~5% of the households use paraffin as a primary energy source for cooking and heating activities, respectively. To a lesser degree gas and small quantities of wood are used as sources of energy for domestic activities.

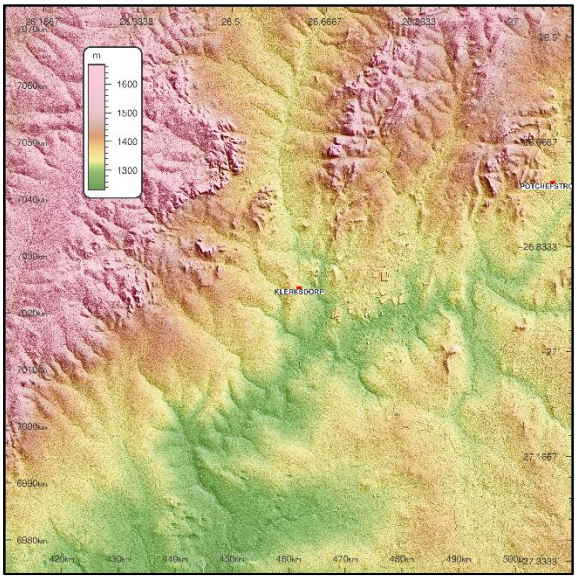
The SAWS Klerksdorp meteorological station (AMS-04) is the nearest long-term monitoring station, situated a mere 2km east-south-east from the centre of Jouberton. The station is located 1329 m.a.m.s.l. The data obtained from this station covers an 18 year period (1992-2010) and are summarised in *Table B.2.*

The region typically has hot summers and cool winters with extreme temperatures ranging from very cold to very hot. The average of the daily mean summer temperatures ranges between ~21 and ~22°C while winter temperatures range between ~10 and 13°C *(Figure 2.10.a)*. During summer the average of the daily maximum temperature range from ~28 to 29°C with average daily minimums ranging from ~15 to 17°C. During winter these can reach between ~19 to 22°C and ~1 to 5°C, respectively. However, during summer the mean highest maximums range between ~36 and 43°C while the mean lowest minimums range from ~10 to 13°C. Throughout winter these temperatures range from ~26 to 34°C and ~-2 to -4°C. The lowest minimum recorded during this period was -7.8 °C on 1 August 2000.

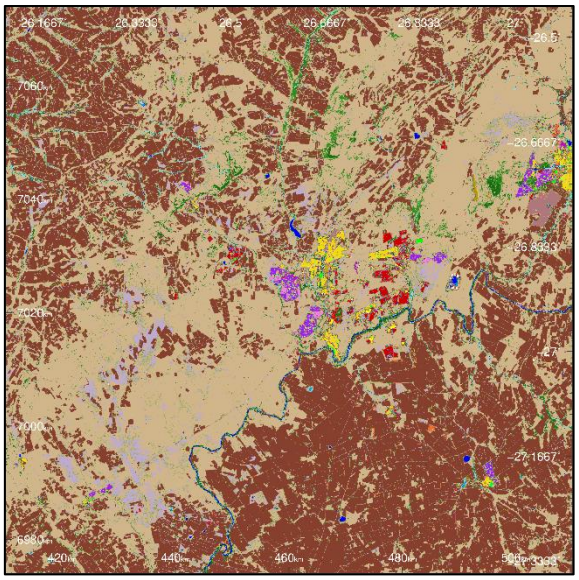
a) Population Density



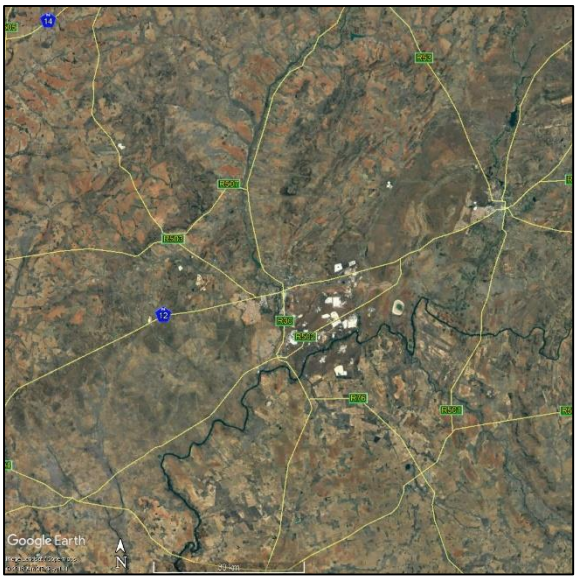
b) Topography



c) Land Cover

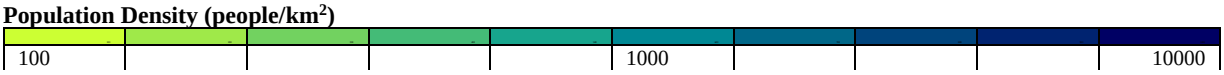


d) Aerial Photograph



Legend:

Population Density (people/km²)



Elevation (m)

Land Use

Grassland	46.2%	Cultivated Commercial Field	43.7%	Wetlands	0.8%
Mines	0.4%	Thicket/Dense Bush	1.5%	Woodland/Open Brush	0.8%
Plantations	0.4%	Urban Residential	0.3%	Water Permanent	0.2%
Bare Bone Vegetation	10.3 km²	Low Scrubland	4.5%	Urban Township	0.3%
Urban Built-up	6.3 km²	Urban Industrial	15.9 km²	Indigenous Forest	N/A
Mines Water	1.2 km²	Water Seasonal	5.3 km²	Urban Smallholding	0.3%
Urban Commercial	14.6 km²	Urban Informal	11.7 km²	Urban Sports	8.8 km²
Urban Village	3.6 km²	Erosion	1.7 km²	Urban Schools	6.9 km²
Cultivated Orchard	4.6 km²	Mines Buildings	3.3 km²	Cultivated Subsistence	<0.1 km²

Figure 2.9. Jouberton settlement (50km²) represented by a) the population density, b) topography, c) land cover, and d) aerial photographs.

There are approximately 67 and 29 days per year that reach temperatures above 30°C and below 0°C, respectively. Jouberton experiences more extreme high temperatures compared to KwaDela and KwaZamokuhle, which is located approximately 315km east-north-east of Jouberton.

The relative humidity is highest during autumn and summer months *(Figure 2.10.b)*. Similarly to KwaDela and KwaZamokuhle the diurnal pattern indicates that the relative humidity is highest during the morning periods and decreases toward mid-afternoon (14h00).

Jouberton is also located within a summer rainfall region and experiences similar precipitation trends to KwaDela and KwaZamokuhle *(Figure 2.10.c)*. However, the total precipitation received is ~460mm, which is almost 300mm less rainfall per year than received by KwaDela and KwaZamokuhle.

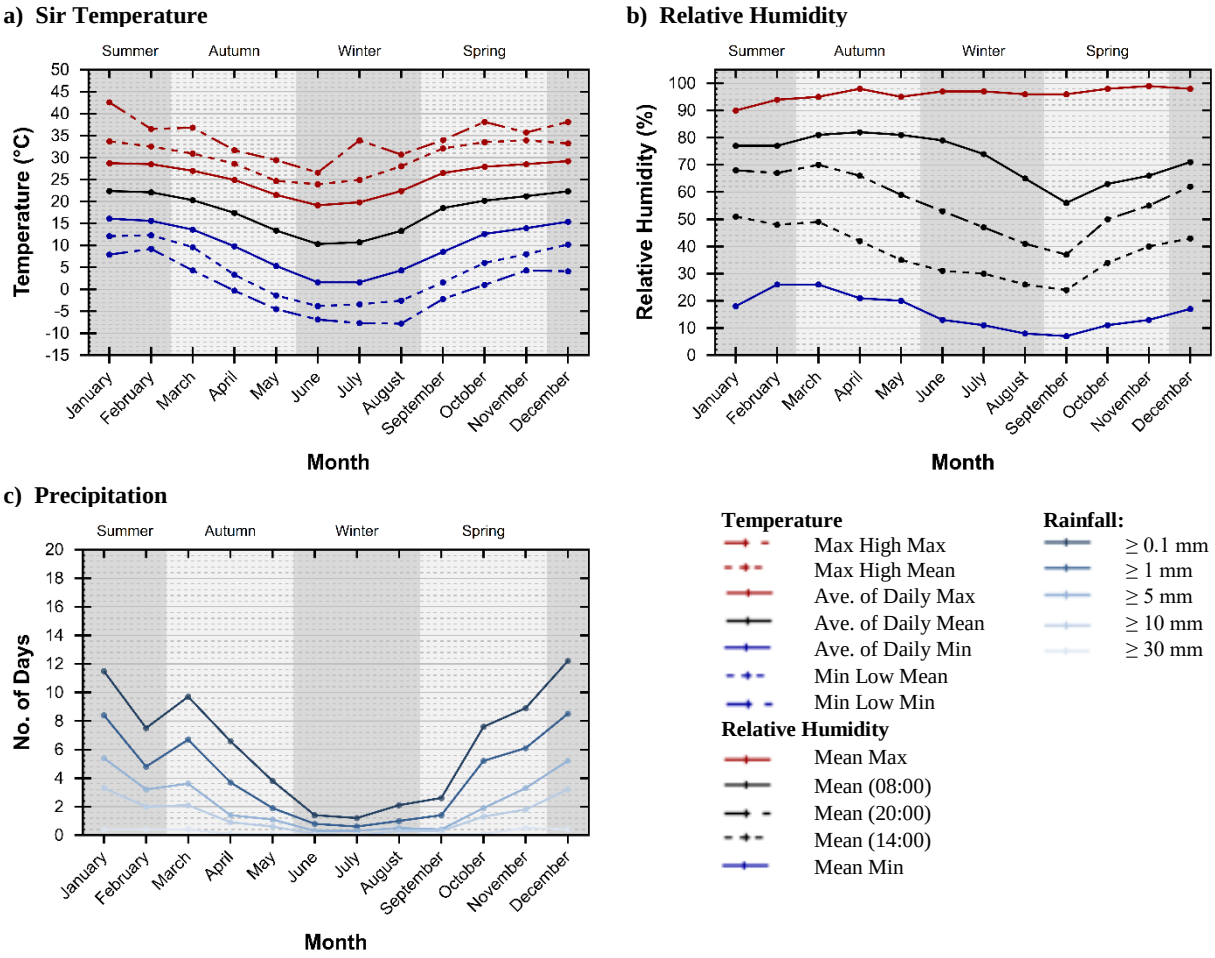


Figure 2.10. The yearly trend in the climatic conditions (1981-2010) for Klerksdorp including a) air temperature, b) relative humidity, and c) precipitation *(South African Weather Service, 2018)*.

2.2.2.4. Agincourt

Agincourt (-24.810546°S; 31.253114°E) is located in the rural northeastern region of Mpumalanga and falls under the jurisdiction of the Bushbuckridge Local Municipality. The area has been part of the Health and Socio-Demographics Surveillance System (HDSS) since the early 1990s, which provides a platform for conducting research linked to a geographically defined population and includes observational- and interventional cohort studies. The HDSS consists of different small areas spread across a large area, thus the population density is low. Four villages were selected within the Agincourt region, namely Cunningmoore A, Croquet Lawn A, Merry Pebble Stream, and Rolle. The topography surrounding the settlement (50km^2) *(Figure 2.11.b)* varies between ~200 and 2000 m.a.m.s.l. The region is flatter with rolling hills toward the east, compared to mountainous areas in the west.

It is dominated by woodland/open bush areas (48.2%) and denser bush (20.8%) in the low-lying areas to the east. This area also forms part of the Kruger National Park. Plantations (10.1%) are found at higher elevations in the west *(Figure 2.11.c)*.

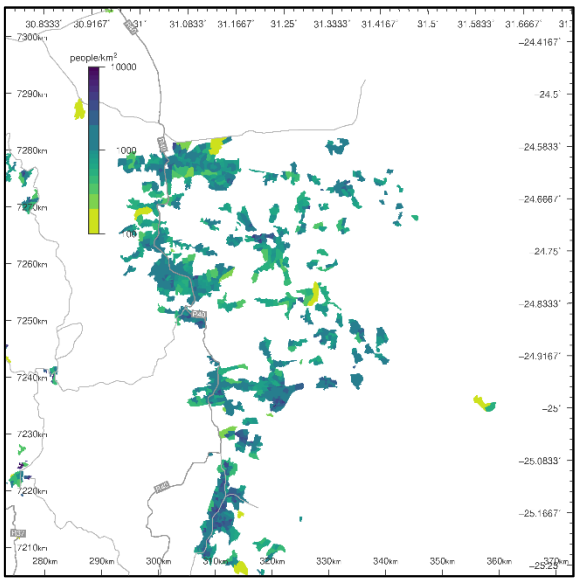
The villages are spread out over a large area resulting in low to moderate populations densities for individual villages *(Figure 2.11.a)*. There are ~21 000 people living in ~5 000 households. The majority (~52%) of the population are below 19 years of age. There is a high rate of poverty with ~20% of households having no income and ~65% of having a monthly income below R3 200. Most of the houses are formal brick (~96%) houses with ~4% of the structures in the community being of a traditional nature. The average household size ranges between one and four persons with ~38% of households having more than four occupants.

The settlement is electrified, however, ~45% and ~12% of the households use wood as a primary energy source for cooking and heating activities.

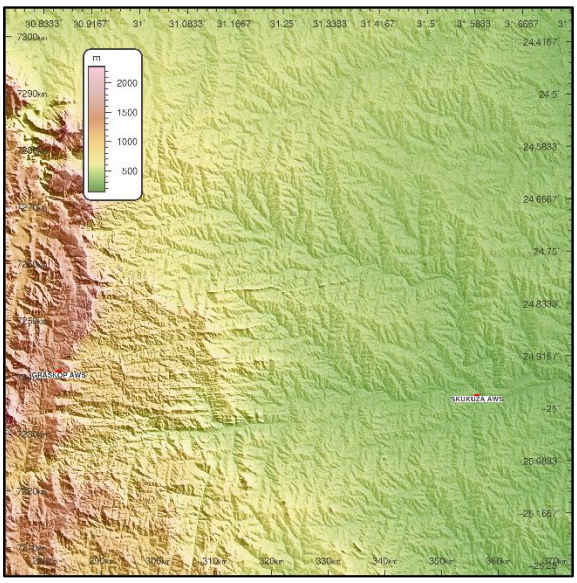
The SAWS Phalaborwa Airport meteorological station (AMS-05) is the nearest long-term monitoring station to Agincourt and is located ~80km to the north of the settlement at 432 m.a.m.s.l. The data obtained from this station covers a 29 year period (1981-2010) and are summarised in ***Error! Reference source not ound.***.

The region typically has hot summers and warm winters. The average of the daily mean summer temperatures ranges between ~24 and ~26°C while winter temperatures range between ~16 and 19°C *(Figure 2.12.a)*. However, during summer the mean highest maximums range between ~41 and 43°C while the mean lowest minimums range from ~15 to 18°C. Throughout winter these temperatures range from ~34 to 38°C and ~4 to 6°C. The lowest minimum recorded during this period was 0.6 °C on 30 June 1994. There are approximately 148 and zero days per year that reach temperatures above 30°C and below 0°C, respectively.

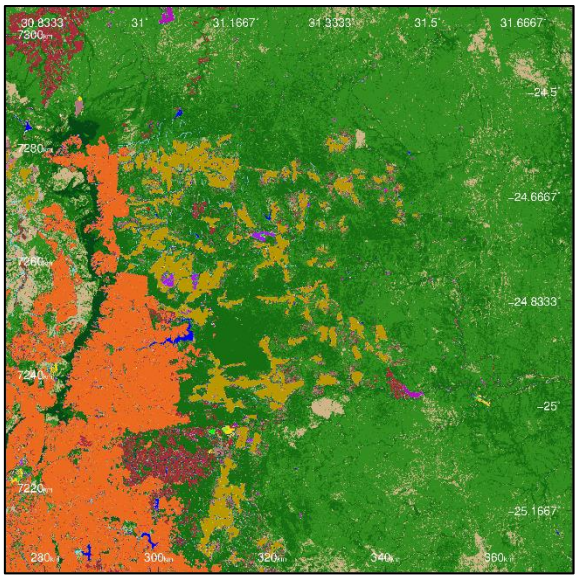
a) Population Density



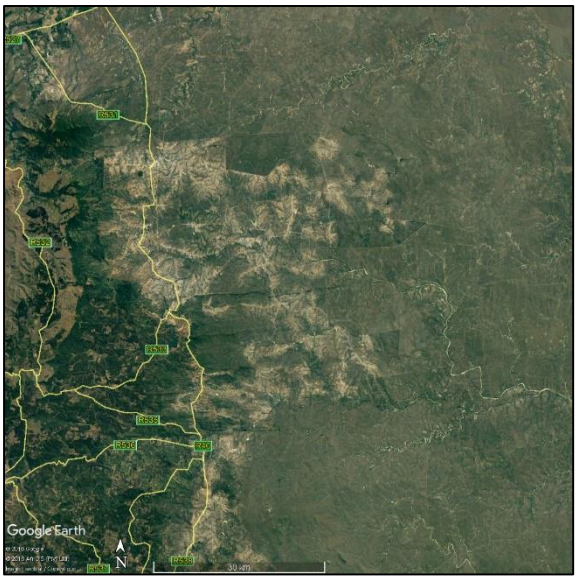
b) Topography



c) Land Cover

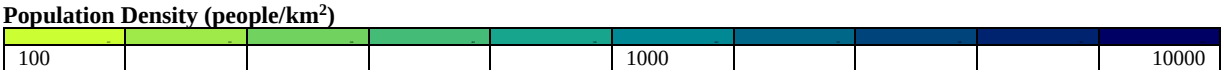


d) Aerial Photograph



Legend:

Population Density (people/km²)



Elevation (m)

Land Use

Grassland	11.0%	Cultivated Commercial Field	0.8%	Wetlands	0.6%
Mines	3.4 km²	Thicket/Dense Bush	20.8%	Woodland/Open Brush	48.2%
Plantations	10.1%	Urban Residential	0.2%	Water Permanent	0.2%
Bare Bone Vegetation	0.1%	Low Scrubland	0.5%	Urban Township	0.2%
Urban Built-up	0.2%	Urban Industrial	7.1 km²	Indigenous Forest	0.9%
Mines Water	<0.1	Water Seasonal	1.0 km²	Urban Smallholding	0.1%
Urban Commercial	4.7 km²	Urban Informal	4.1 km²	Urban Sports	5.6 km²
Urban Village	2.9%	Erosion	5.3 km²	Urban Schools	1.7 km²
Cultivated Orchard	0.8%	Mines Buildings	<0.1 km²	Cultivated Subsistence	0.6%

Figure 2.11. Agincourt settlement (50km²) represented by a) the population density, b) topography, c) land cover, and d) aerial photographs.

The relative humidity is highest during summer months *(Figure 2.12.b)*. The area has around ~400mm of precipitation per year with a maximum of 763 mm measured for 2000 and a minimum of 144 mm for 1994. Majority of the rainfall occurs from late spring to early autumn, with the highest rainfall occurring in summer *(Figure 2.12.c)*.

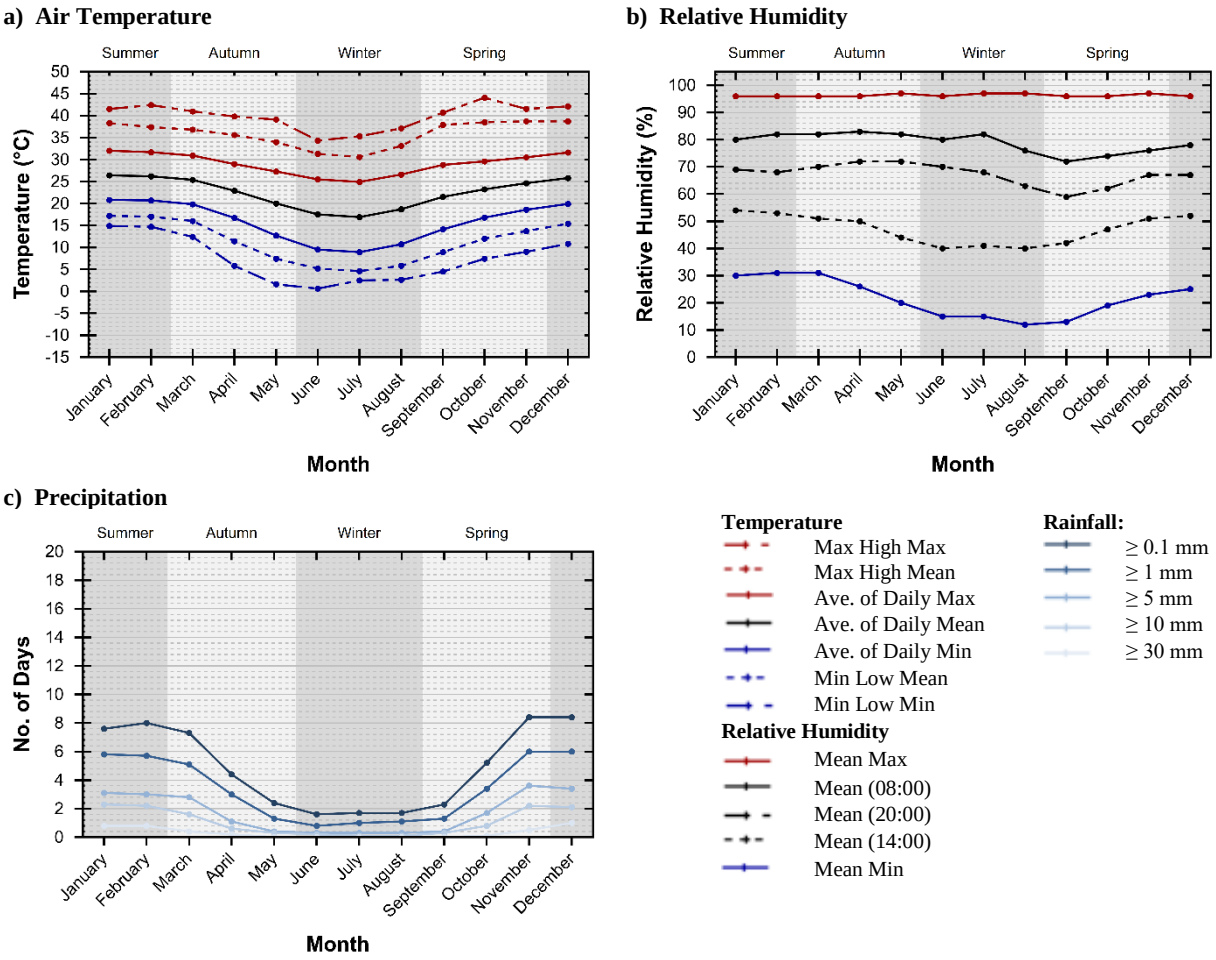


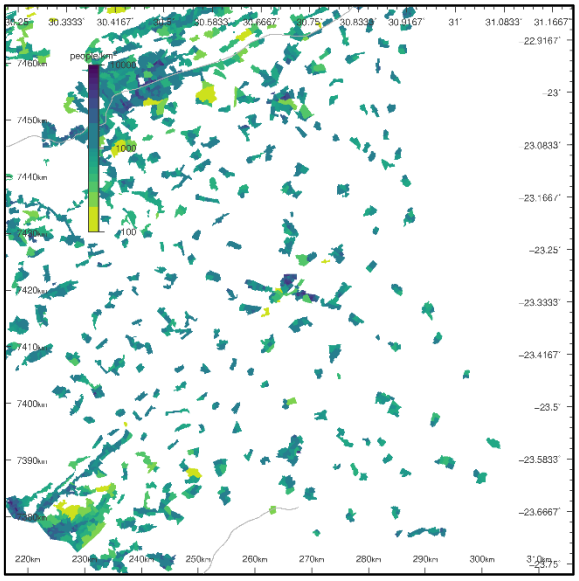
Figure 2.12. The yearly trend in the climatic conditions (1981-2010) for Phalaborwa including a) air temperature, b) relative humidity, and c) precipitation *(South African Weather Service, 2018)*.

2.2.2.5. Giyani

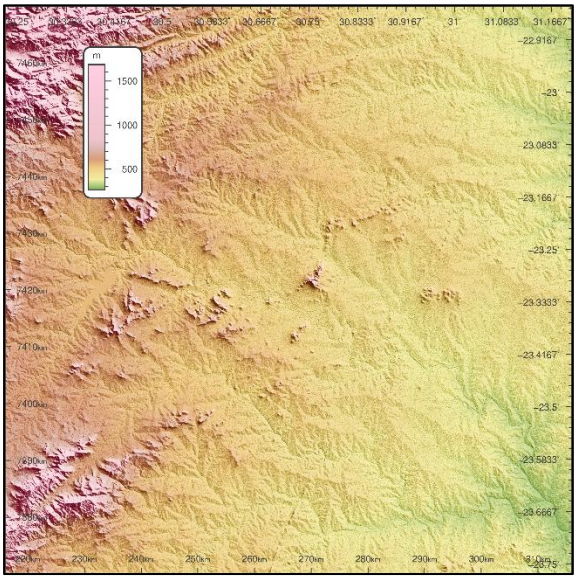
Giyani (-23.308208°S; 30.707208°E) is situated ~170km to the north-north-west of Agincourt in the Limpopo province. It falls within the Great Giyani Local Municipality. Four villages were included in this study, namely Ka-Tomu, Ka-Siyandani, Ka-Maswanganyi, and Ka-Dizingidzingi. The topography surrounding the settlement (50km^2) *(Figure 2.13.b)* varies between ~300 and 1700 m.a.m.s.l.

The region is flatter with rolling hills toward the east and south-east, compared to mountainous areas in the north and north-west. It is dominated by woodland/open bush areas (32.8%), dense bush (25.7%), grasslands (19.9%), and cultivated lands (7.2%) *(Figure 2.13.c)*.

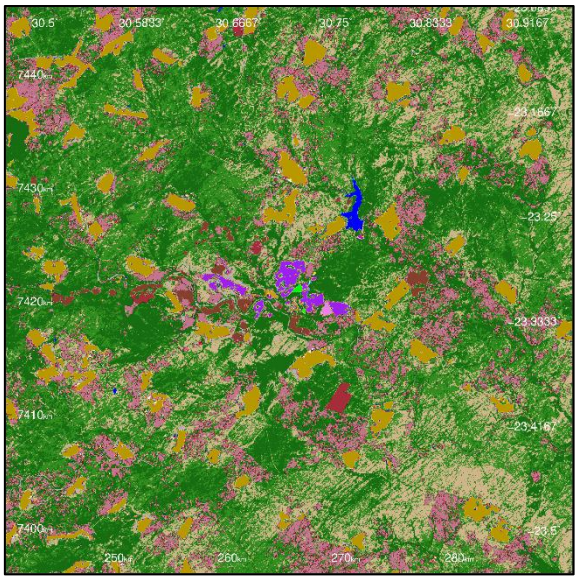
a) Population Density



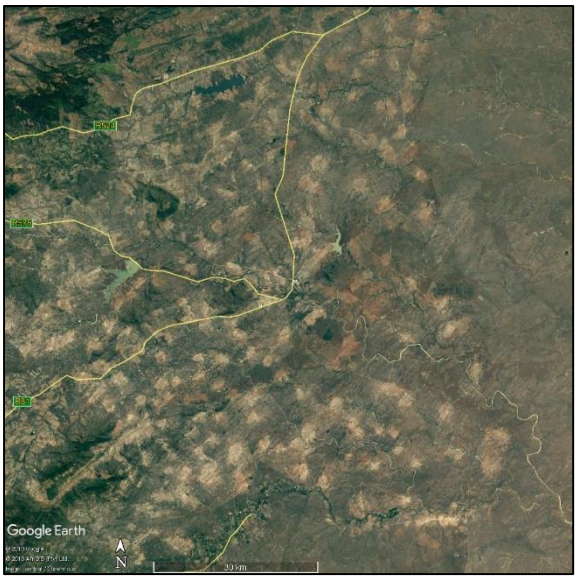
b) Topography



c) Land Cover

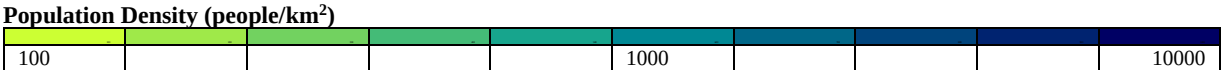


d) Aerial Photograph

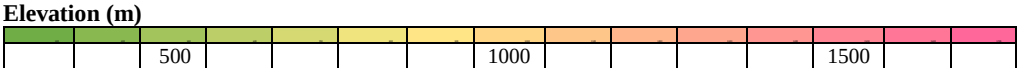


Legend:

Population Density (people/km²)



Elevation (m)



Land Use

Grassland	19.9%	Cultivated Commercial Field	0.7%	Wetlands	1.6 km²
Mines	3.0 km²	Thicket/Dense Bush	25.7%	Woodland/Open Brush	32.8%
Plantations	0.8%	Urban Residential	0.2 km²	Water Permanent	0.4%
Bare Bone Vegetation	4.6 km²	Low Scrubland	0.5%	Urban Township	0.2%
Urban Built-up	3.6 km²	Urban Industrial	0.9 km²	Indigenous Forest	0.5%
Mines Water	0.5 km²	Water Seasonal	1.0 km²	Urban Smallholding	N/A
Urban Commercial	2.6 km²	Urban Informal	0.7 km²	Urban Sports	0.6 km²
Urban Village	9.1%	Erosion	0.4%	Urban Schools	N/A
Cultivated Orchard	1.7%	Mines Buildings	N/A	Cultivated Subsistence	7.2%

Figure 2.13. Giyani settlement (50km²) represented by a) the population density, b) topography, c) land cover, and d) aerial photographs.

There are ~15 000 people living in ~3 500 households, resulting in low to moderate population density *(Figure 2.13.a)*. The majority (~60%) of the population are below 24 years of age. There is a high rate of poverty with ~12% of households having no income and ~70% of having a monthly income below R3 200. Most of the houses are formal brick (~92%) houses with ~5% of the structures in the community being of a traditional nature. The average household size ranges between one and four persons with ~40% of households having more than four occupants.

The settlement is electrified, however, ~84% and ~55% of the households use wood as a primary energy source for cooking and heating activities. The households also make use of separate outside cooking structures (similar to Agincourt).

The SAWS Thohoyandou meteorological station (AMS-07) is situated ~40km to the north-west of Giyani at 614 m.a.m.s.l. The data obtained from this station covers a 28 year period (1983-2010) and are summarised in *Table B.4*.

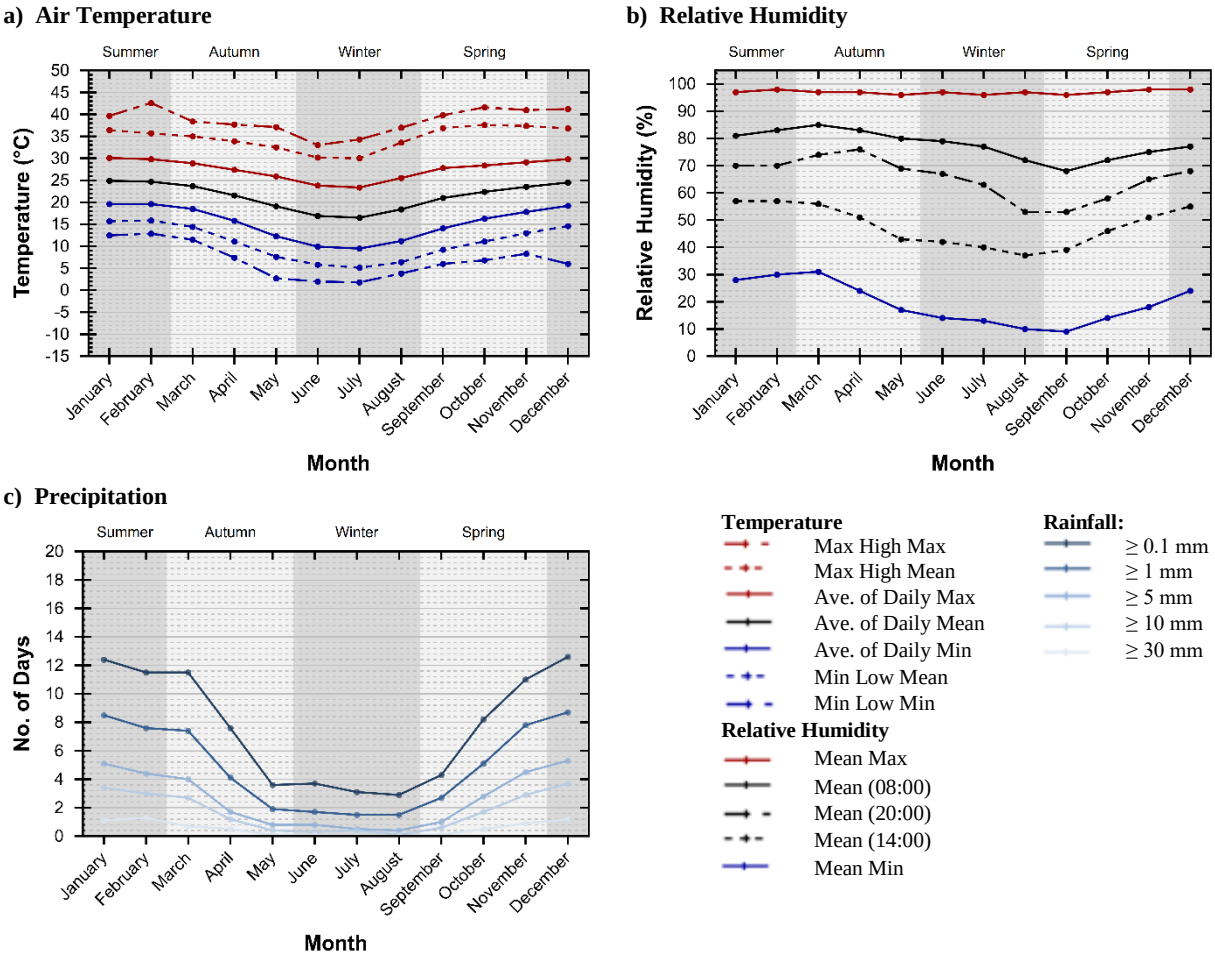


Figure 2.14. The yearly trend in the climatic conditions (1981-2010) for Thohoyandou including a) air temperature, b) relative humidity, and c) precipitation *(South African Weather Service, 2018)*.

The average of the daily mean summer temperatures is ~25°C while winter temperatures range between ~13 and 15°C *(Figure 2.14.a)*. During summer the average of the daily maximum temperature range from ~29 to 31°C with average daily minimums is ~19°C. During winter these can reach between ~23 to 25°C and ~9 to 12°C, respectively. However, during summer the mean highest maximums range between ~39 and 43°C while the mean lowest minimums range from ~14 to 16°C. Throughout winter these temperatures range from ~33 to 37°C and ~5 to 7°C. The lowest minimum recorded during this period was 1.8 °C on 2 June 1996. There are approximately 119 and zero days per year that reach temperatures above 30°C and below 0°C, respectively.

The relative humidity is highest during summer and early autumn months *(Figure 2.14.b)*.

The area has around ~760mm of precipitation per year with the majority of the rainfall occurring from late spring to early autumn, with the highest rainfall occurring in summer *(Figure 2.14.c)*. This trend is similar to Agincourt, however, the total rainfall per year differ by ~360mm.

2.3. Experimental procedure to characterise indoor air quality

2.3.1. Household selection and recruitment

The household requirement process was dependent on the individual project, however, all the households were selected by random sampling. The primary selection criteria for individual projects are as follows:

Households in KwaDela and KwaZamokuhle were randomly selected from a stratified subsample of households, which participated in a general household survey, based on the census sub-places within the settlement. The selected households used solid fuels (coal) for space heating and cooking during winter months and were built through the Reconstruction and Development Programme (RDP). More specifically the house was i) rectangular in shape that did not exceed 50m^2, ii) had walls built from cement bricks or clay, iii) roof constructed from asbestos or corrugated iron, iv) did not have any additional extensions built onto the house, v) may have a lean-to shack to one facade which is not north, and vi) had no open electrical wiring in the ceiling cavity. There were no specific criteria relating to the number of residents for each house. Due to the larger study being a thermal intervention-based study, the households selected for the indoor air quality monitoring included various types of retrofits as well as a number of control (coal using) households.

The households in Agincourt and Jouberton had to have at least three permanent residents who have resided in the community for a minimum of one year prior to the commencement of the study and who continued to stay in the community throughout the duration of the study. In addition, no less than 50% of the selected household should have one child below 5 years of age. If more than one individual in the house did not consent the house was deemed non-eligible for inclusion in the study. An initial sample of two-hundred

houses were randomly selected within each settlement. The households were then visited by trained field workers to verify the above-mentioned inclusion criteria. A final sample of 50 households per year were enrolled in each settlement if, however, the target sample size was not met additional households were recruited. There were no specific inclusion criteria related to the house structure itself, thus the houses used in these settlements were not standardised.

The houses in Giyani were selected from four villages (Ka-Tomu, Ka-Siyandani, Ka-Maswanganyi, Ka-Dizingidzingi) situated around the town. A cluster sampling method was used to identify 100 households in each of the villages. The nine households included in the indoor monitoring was randomly selected from those identified in the cluster sampling. Similarly to Agincourt and Jouberton, the houses from this settlement was not standardised.

Due to the variability in the types of households included in the study, the structures were categorised into three main dwelling types. Houses that were built by the residents themselves are referred to as 'Formal' *(Figure 2.15.a)*. Houses built through the RDP program that do not have any additional extensions built onto the original building are classified as "Formal RDP" *(Figure 2.15.b)*, while "Informal" houses are those constructed from corrugated iron and typically referred to as shacks *(Figure 2.15.c)*. As all the houses in the study were electrified, the households were sub-divided into three categories based on their solid fuel use practices. These classes included houses that actively take part in indoor solid fuel burning (ISFB), or outdoor solid fuel burning (OSFB) as well as non-solid fuel burning (NSFB) households.

a) Formal **b) Formal RDP** **c) Informal**

Figure 2.15. Dwelling type classes: a) formal house (Giyani), b) formal RDP (KwaDela), and c) informal (KwaDela) household structures (photographs by B. Language 2016-2017).

2.3.1.1. Demographics of sampled households compared the national census

A total of two hundred and fifty-one (251) households were sampled over the five year period. The households were categorised according to the type of house and fuel use, as described in *Section 2.3.1*.

The sample consisted of two hundred and seven (207) formal, thirty-three (33) formal RDP, and eleven (11) informal structures. The majority of the formal houses were set in Jouberton (101), Agincourt (97),

and Giyani (9), while the formal RDP structures were located in KwaDela (23) and KwaZamokuhle (10). Informal residences sampled were situated in Jouberton (5) and Agincourt (6).

Households can also be classified by fuel use. Of the selected houses fifty (50) were indoor solid fuel burning (ISFB), one hundred and fifteen (115) non-solid fuel burning (NSFB), and eighty-six (86) outside solid fuel burning (OSFB). The fuel use sub-categorisation of households per settlement is summarised in *Table 2.1*. ISFB houses were sampled in four settlements (KwaDela, KwaZamokuhle, Jouberton, and Agincourt). The NSFB households were spread across both the Highveld and Lowveld regions with the majority being situated in Jouberton. The Lowveld region, Agincourt and Giyani, contained all of the OSFB households.

Table 2.1 Number of households sampled per settlement classified by the household type and fuel use.

Household Type & Fuel Class	**Settlements**					**Total**
	KwaDela	**KwaZamokuhle**	**Jouberton**	**Agincourt**	**Giyani**	
Formal	-	-	**101**	**97**	**9**	**207**
ISFB	-	-	8	12	-	**20**
NSFB	-	-	93	10	1	**104**
OSFB	-	-	-	75	8	**83**
Formal RDP	**23**	**10**	-	-	-	**33**
ISFB	16	9	-	-	-	**25**
NSFB	7	1	-	-	-	**8**
Informal	-	-	**5**	**6**	-	**11**
ISFB	-	-	2	3	-	**5**
NSFB	-	-	3	-	-	**3**
OSFB	-	-	-	3	-	**3**
Total	**23**	**10**	**106**	**103**	**9**	**251**

Note: **ISFB** – Indoor Solid Fuel Burning, **NSFB** – Non-Solid Fuel Burning, **OSFB** – Outdoor Solid Fuel Burning

A comparison was done between the questionnaire survey data *(see Section 2.3.2.5.3)* of the two hundred and fifty-one (251) sampled households and the national census 2011 data *(see Section 2.3.2.5.1)* to see how well the sample compared to the dynamics which exists within each of the communities. The annual household income, housing type, household size, and primary energy used for cooking and heating activities were considered.

The individual settlements had high rates of poverty with ~40 to 70% of households *(Figure 2.16.a)* having an annual income less than R38 200 (equivalent to ~R3 183 per month). Approximately 12 to 20% of the above mentioned have no income at all. The study focuses specifically on low-income households (≤R3 200 per month), thus~35 to 90% of the sampled households *(Figure 2.16.b)* fell within this category. Note

that there were households that did not want to disclose the income they receive (unspecified) or declined to answer the question (undisclosed).

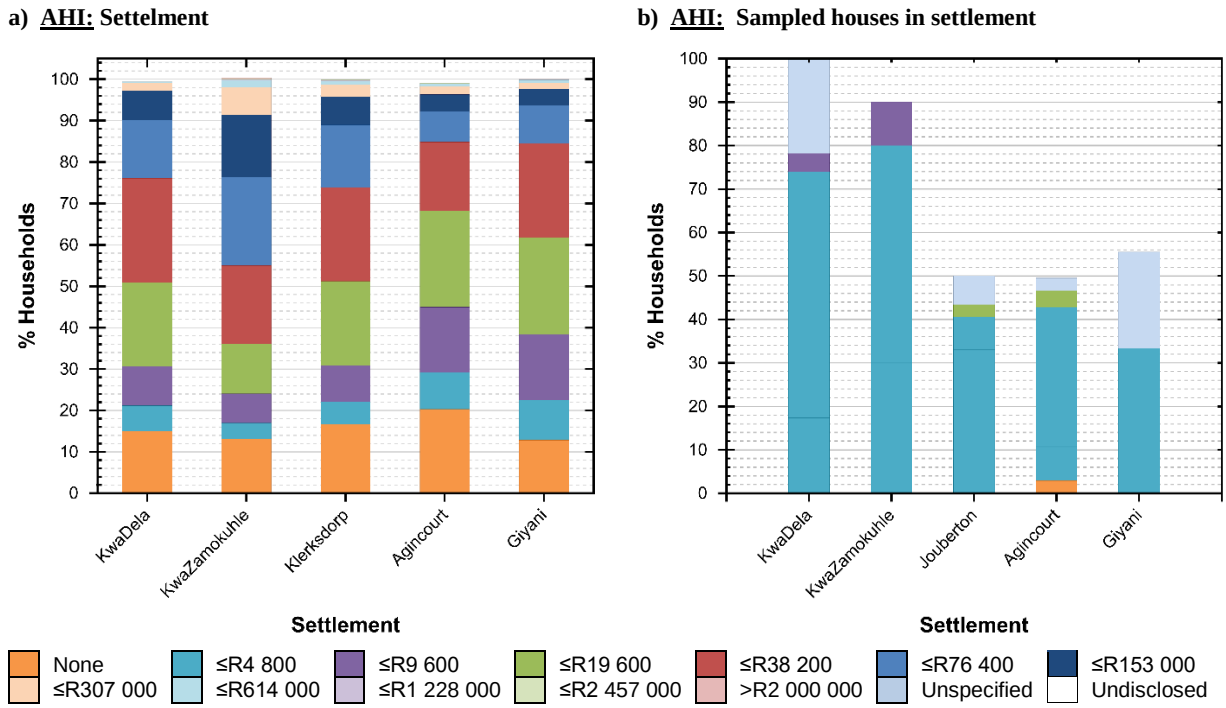


Figure 2.16. Stacked percentages of the annual household income (AHI) for a) the individual sampled settlements *(Statistics South Africa, 2011)*, and b) the sampled households within each settlement (household survey).

The individual settlements consisted of mostly (~70 to 95%) formal housing type constructed from bricks *(Figure 2.17.a)*. Informal housing was more prevalent in KwaDela, KwaZamokuhle, and Jouberton, with ~6 to 22% of dwellings. Less than ~2% of households in Agincourt and Giyani were classified as informal. Traditional dwellings were more common in Agincourt and Giyani (~2 to 5%), compared to KwaDela, KwaZamokuhle, and Jouberton (~<1%). The dwellings sampled in each settlement consisted mostly of formal brick houses *(Figure 2.17.b)*. The household sample in Jouberton and Agincourt contained ~5% of informal dwelling types, respectively.

Roughly 75 to 83% of households across the individual settlements *(Figure 2.18.a)* has an occupancy level of five (5) people or less, of this ~ 28 to 47% of dwellings had two or fewer occupants. On average the settlements consisted of ~18% of households with between six (6) and (9) residents. Only about 3% of dwellings had ten (10) or more occupants. The occupancy numbers of the sampled dwellings within each settlement is presented in *Figure 2.18.b*. The majority (~67 to 70%) of the households sampled in KwaDela, KwaZamokuhle and Giyani had five (5) or fewer occupants. Due to the selection criteria (dwellings with <3 occupants excluded) used for Jouberton and Agincourt ~44 to 55% of households had between three (3)

and five (5) occupants. Jouberton and Agincourt had a higher percentage (~45 to 54%) of households with more than five (5) occupants, compared to the other three settlements (~20 to 30%).

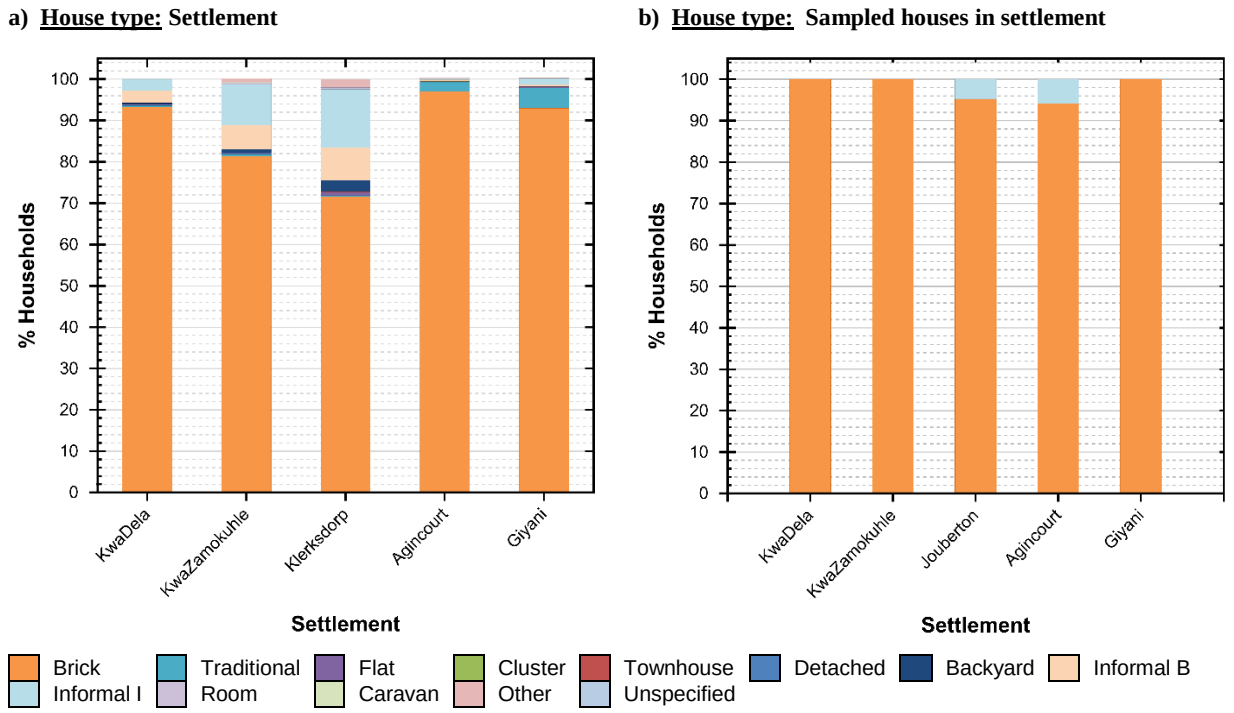


Figure 2.17. Stacked percentages of the household type for a) the individual sampled settlements *(Statistics South Africa, 2011)*, and b) the sampled households within each settlement (household survey).

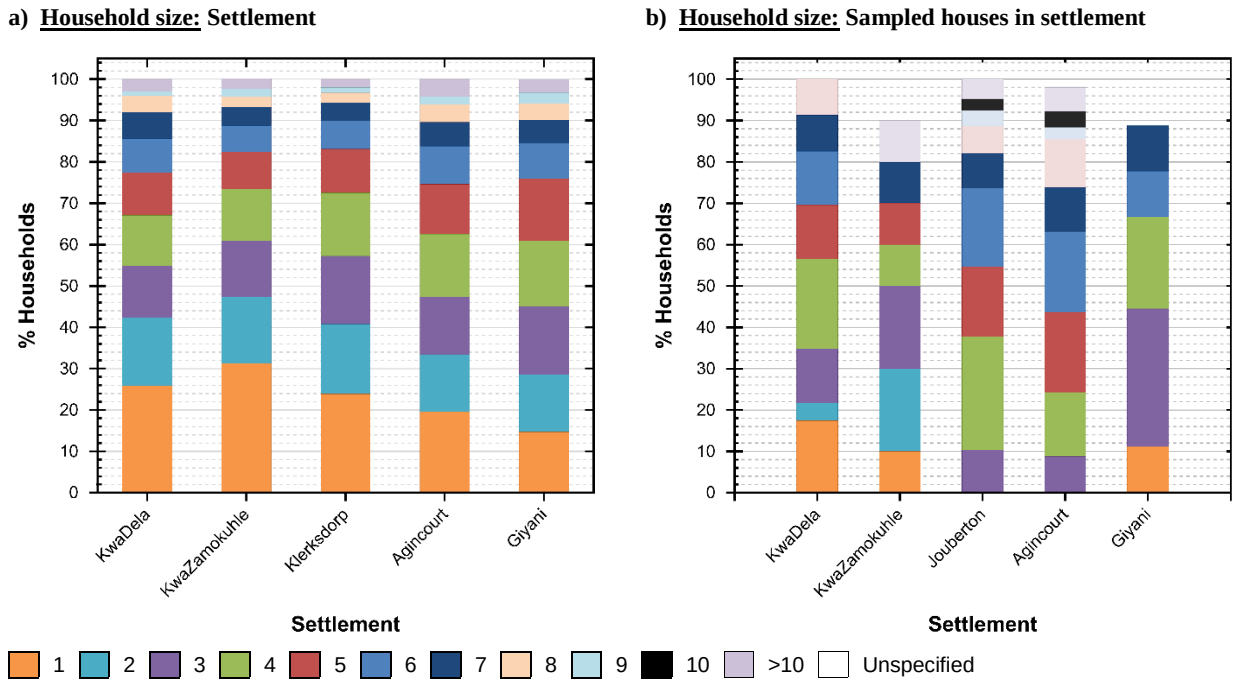


Figure 2.18. Stacked percentages of the household size for a) the individual sampled settlements *(Statistics South Africa, 2011)*, and b) the sampled households within each settlement (household survey).

The primary energy used for cooking (*Figure 2.19.a*) and heating (*Figure 2.19.c*) activities in the Highveld regions is electricity. Roughly ~50 to 65% of household in the rural communities of KwaDela and KwaZamokuhle use electricity, while the urbanised settlement of Jouberton has ~70 to 85% of dwellings using primarily electricity. In the Lowveld regions, electricity is used by ~50 to 60% of houses in Agincourt and ~15 to 40% of dwellings in Giyani. Coal is used by ~30 to 45% of households in KwaDela and KwaZamokuhle. Paraffin is the second most popular choice (~11% of houses) in Jouberton. Wood is used for cooking by ~50 to 85% of dwelling in Agincourt and Giyani, and less (~11 to 55%) so for heating.

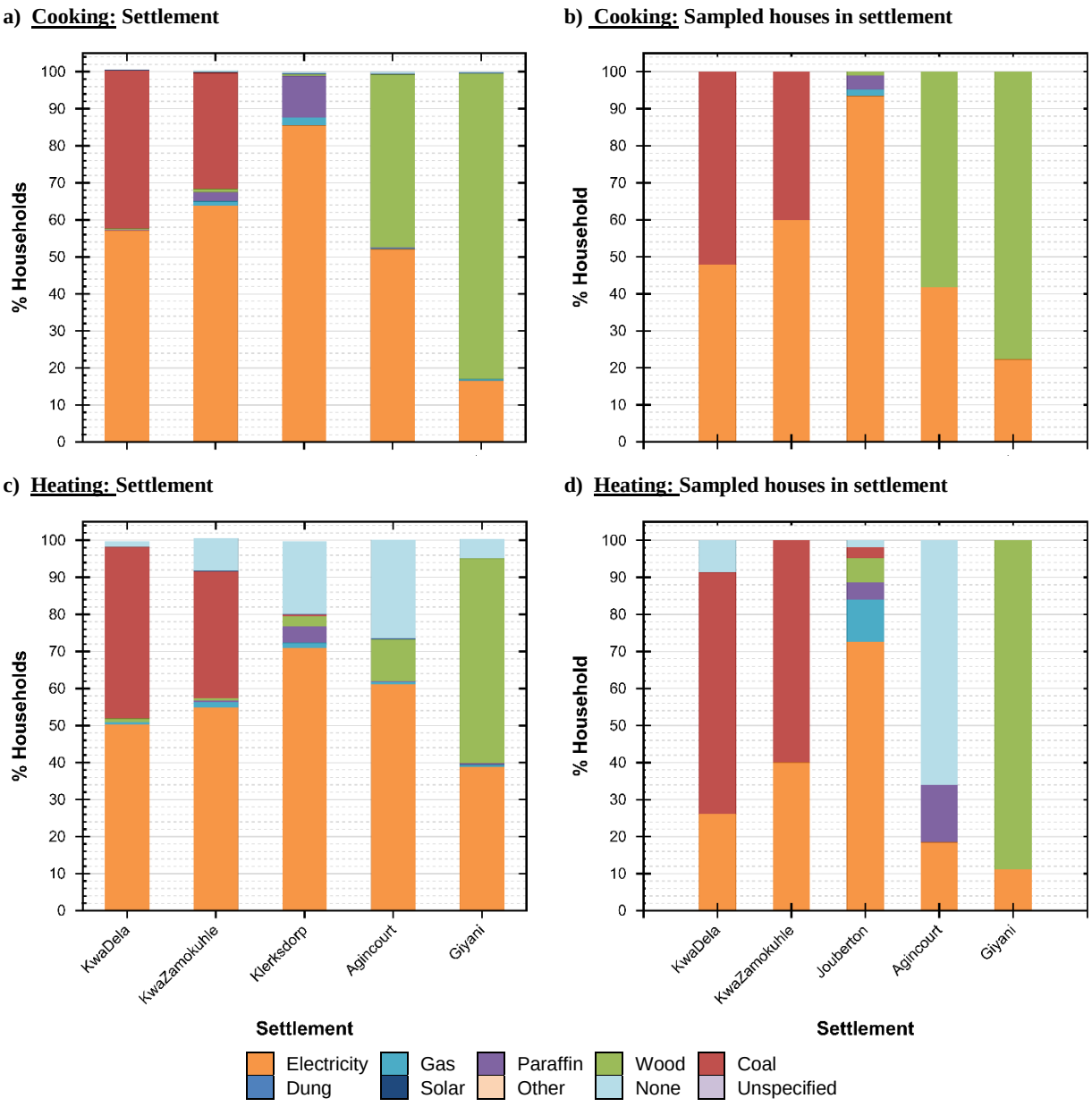


Figure 2.19. Stacked percentages of the primary energy sources used for cooking (a-b) and heating (c-d) for the individual sampled settlements (a and c) *(Statistics South Africa, 2011)*, and the sampled households within each settlement (b and d) (household survey).

The primary energy used for cooking and heating activities in the sampled households of each settlement is shown in *Figure 2.19.b* and *d*. Roughly ~25 to 60% of the sampled houses in KwaDela and KwaZamokuhle use electricity, while the urbanised settlement of Jouberton has ~70 to 95% of the sampled dwelling using primarily electricity. In the Lowveld regions (Agincourt and Giyani), electricity is used by ~10 to 40% of sampled houses. Coal is used by ~40 to 65% of sampled households in KwaDela and KwaZamokuhle. Paraffin is the second most popular choice (~5% of houses) in Jouberton. Wood is used for by ~60 to 90% of sampled dwellings in Agincourt and Giyani.

Based on the above comparisons between the national census data and household questionnaire survey data it can be concluded that the sampled households are a good comparative sample of typical conditions within the five settlements. All the houses were not subject to the same monitoring and sampling activities, thus the specific households included in each method are discussed in *Sections 2.3.2.1*, *0*, and *0*.

2.3.2. Data collection and laboratory analysis

The study was carried out over a period of five years which included twenty-one (21) individual sampling campaigns conducted between July 2013 and November 2017, as summarised in *Table 2.2*.

The sampling campaigns were done on a seasonal basis, where the winter period was considered to be the worst-case scenario for ambient and indoor air pollution while summer represented the best case scenario with regards to the level of particulate pollution. Ten (10) winter and nine (9) summer sampling campaigns were conducted between 2013 and 2017. There were two (2) instances in which sampling took place during spring which is thought of as a transitional season. The methods used during each individual campaign are also indicated in *Table 2.2*. The individual data collection methods are discussed in more detail below.

Table 2.2 Measurements conducted during each field campaign for individual settlements sampled in the Highveld and Lowveld regions.

Region	Settlement	No.	Season	Year	Installation	Decommission	M-I	M-II	M-III		
									E-I	E-II	E-III
Highveld	KwaDela	1	Winter	2013	2 July	27 September	√	-	-	-	-
		2	Summer	2014	10 February	6 May	√	-	-	-	-
		3	Winter	2014	10 July	18 September	√	-	-	-	-
		4	Summer	2015	11 February	13 April	√	√	√	√	-
Highveld	KwaZamokuhle	5	Winter	2015	7 July	21 July	√	√	√	√	-
		6	Spring	2015	2 September	26 November	√	-	-	-	-
		7	Summer	2016	24 February	19 April	√	√	√	√	-
		8	Winter	2016	12 July	9 September	√	-	-	-	-
		9	Winter	2017	26 July	16 August	√	√	√	-	-

		10	Summer	2017	1 November	20 November	√	√	√	-	-
	Jouberton	11	Summer	2016	14 April	20 May	√	√	√	-	-
		12	Winter	2016	14 July	18 August	√	√	√	-	-
		13	Summer	2017	1 February	9 March	√	√	√	-	-
		14	Winter	2017	1 June	6 July	√	√	√	-	-
Lowveld	Agincourt	15	Summer	2016	14 April	20 May	√	√	√	-	-
		16	Winter	2016	14 July	18 August	√	√	√	-	-
		17	Summer	2017	1 February	9 March	√	√	√	-	-
		18	Winter	2017	1 June	6 July	√	√	√	-	-
	Giyani	19	Spring	2016	6 September	15 September	√	√	√	-	√
		20	Summer	2017	6 February	8 March	√	√	√	-	-
		21	Winter	2017	3 July	31 July	√	√	√	-	-

M-I – Continuous Monitoring; **M-II** – Gravimetric Sampling; **M-III** – Collocated Sampling; **E-I** – Photometric Calibration Factor I; **E-II** – Instrument Comparison II; **E-III** – Size Fraction Comparison

2.3.2.1. Continuous monitoring with photometric instrumentations (Objectives II)

2.3.2.1.1. Instrumentation

The instruments used for the continuous monitoring of the mass concentrations of indoor particulate matter are the DustTrak Model 8520 (DT), DustTrak II Model 8530 (DT II), and the SidePak AM510 (SP) *(Figure 2.20)*.

The instrument sampling flows range from 0.7 to 2.4 L.min^{-1}, however, the SidePak has a maximum flow of 1.8 L.min^{-1} and the DustTrak Model 8520 a minimum operating flow of 1.4 L.min^{-1}. All three instruments have a particle size range of 0.1 to ~10 µm. The lower limit of detection for the instruments is 0.001 mg.m^{-3} while the upper limit in the detection rage is 20 (SP), 100 (DT, and 400 (DT II) mg.m^{-3} respectively. The laser beam of DT and DT II monitors operates at a 780nm wavelength and the SidePak monitor at a 670nm wavelength *(TSI Incorporated, 2010, 2012a, 2012b, 2014)*.

a) **b)** **c)**

Figure 2.20. Continuous photometric monitoring instruments, namely, a) DustTrak Model 8520, b) DustTrak II Model 8530, and c) SidePak AM510 *(TSI Incorporated, 2010, , 2012a, , 2014)*.

The temperature (0 to 50°C) and relative humidity (0 to 95% non-condensing) at which the instruments operate are sufficient for South African climatic conditions. The concentrations measured are influenced by temperature as the instruments have a temperature coefficient of ±0.001 $mg.m^{-3}$ per degree Celsius for the DT/DT II and ±0.005 for the portable SP. The zero stability of the instruments has a ±0.001 $mg.m^{-3}$ drift over a 24-hour period at a time constant of 10 seconds *(TSI Incorporated, 2010, 2012a, 2012b, 2014)*.

These monitoring devices are classified as single-channel basic photometric instruments. Thus, a diaphragm pump continuously draws aerosols into the sensing chamber *(Figure 2.21)*, however, only $^{2}/_{3}$ of the aerosol stream directly enters the sensing chamber. The remaining $^{1}/_{3}$ of the steam is needed as sheath flow, meaning that the aerosol stream flows through a HEPA filter after which it is inserted into the chamber as sheath flow *(TSI Incorporated, 2012b)*.

The main purpose of the sheath air is to keep the optics of the instrument clean and improve instrument response time. Once in the chamber, a sheet of light emitted from a laser diode illuminates the aerosol particles. The particles scatter the light which is focused onto the photodetector by a gold-coated spherical mirror. The mass concentration of aerosol particles is proportional to the voltages provided by the photodetector. The voltage is also multiplied by the calibration constant. The calibration constant is derived from the ratio of known mass concentrations of the Arizona Test Dust (ISO 12103-1, A1 Test Dust) to the voltage response of the aerosol monitor *(TSI Incorporated, 2012b)*.

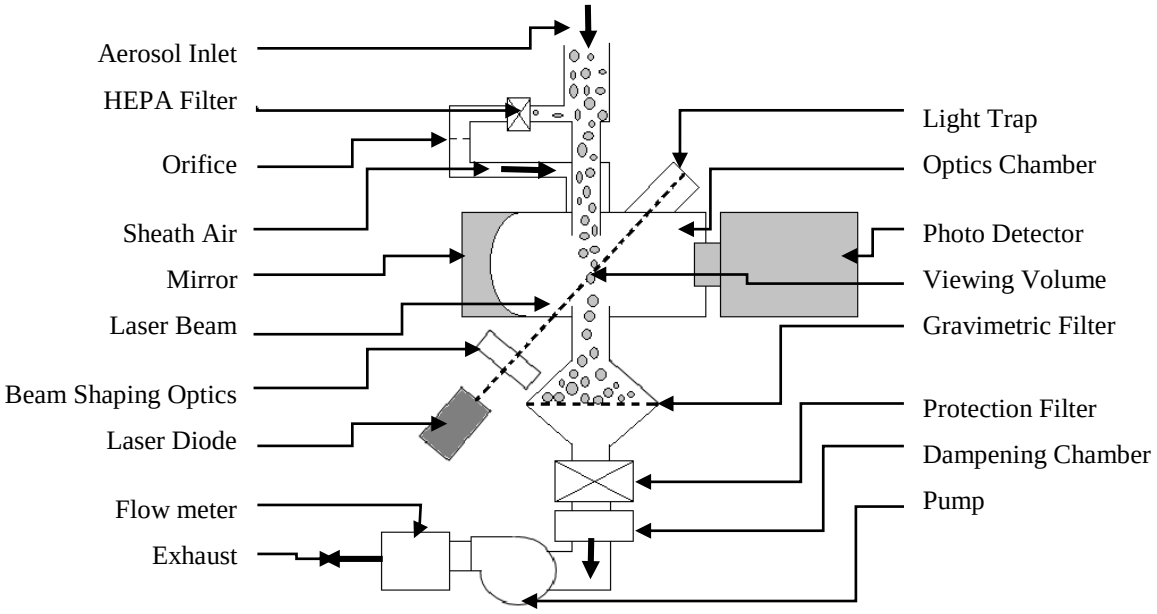


Figure 2.21. DustTrak II Model 8530 aerosol monitor theory of operation diagram *(adapted from TSI Incorporated, 2012b)*.

These monitoring instruments are able to perform size-selective sampling as the instruments are equipped with interchangeable impactors. The respirable fraction, namely particles with a diameter equal to or less than 4µm, is sampled by making use of a Dorr-Oliver cyclone. The Dorr-Oliver cyclone inlet *(Figure 2.22.a)* is an inlet devised to separate the respirable and non-respirable fractions of airborne particulate matter.

The inlet was primarily designed for use in the sampling of airborne particles causing pneumoconiosis lung disease, however, it is now effectively utilised in the monitoring and measurement of all types of particulate matter *(Sensidyne, 1999)*. The inlet itself is constructed from a Nylon material and is 10mm in diameter. The unit comprises of a two-stage cyclone, meaning that as air enters at a flow rate of 1.7 $L.m^{-1}$, the particles are centrifugally separated into the non-respirable and respirable fractions. The larger non-respirable particles are deposited into the grit pot at the bottom of the cyclone *(Sensidyne, 2003)*. The cyclone has a 50% cut point for the 4 µm particle size fraction *(Figure 2.22.c)*. This means that 100% of the 10 µm particle fraction and 50% of the 4 µm fraction is removed by the cyclone *(Sensidyne, 1999)*.

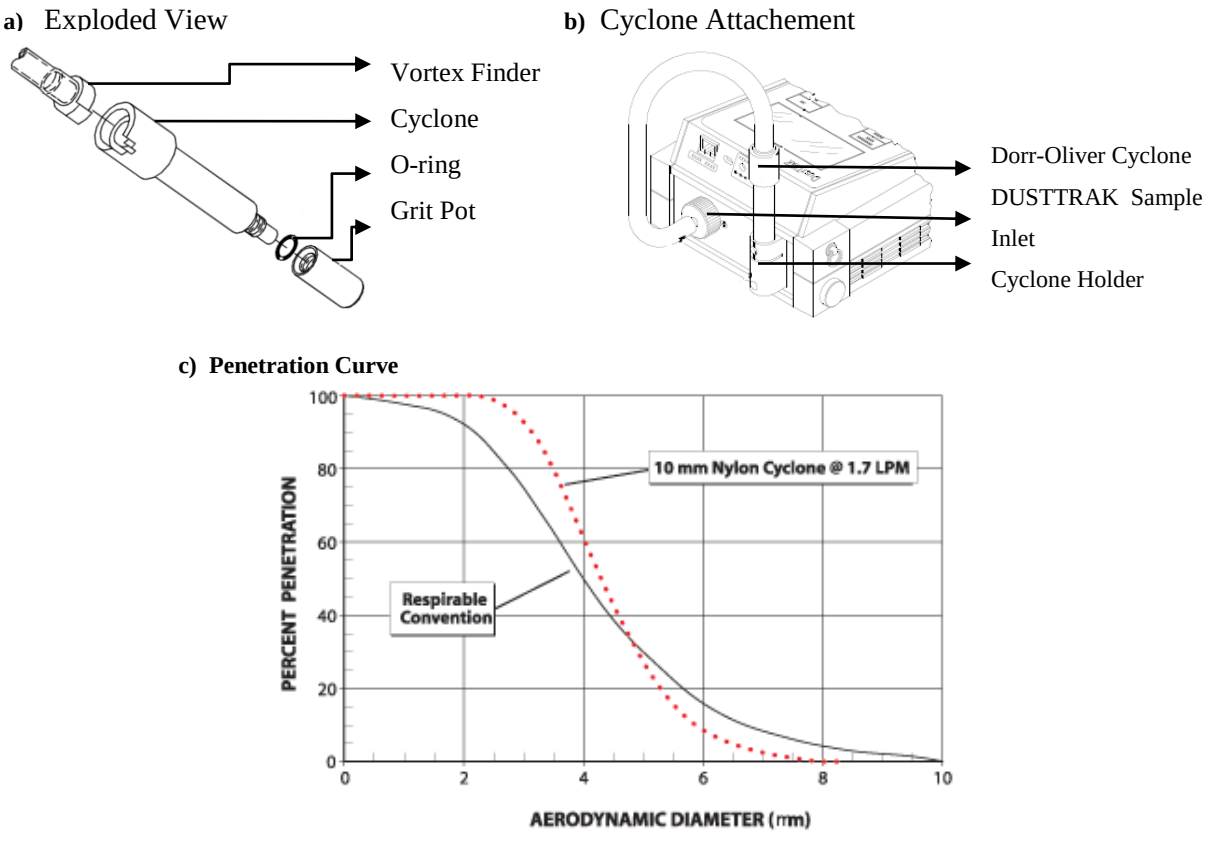


Figure 2.22. a) An exploded view of the 10mm Nylon Dorr-Oliver Cyclone and b) a cyclone attached to an instrument *(TSI Incorporated, 2010)*. c) The penetration curve for the cyclone *(Sensidyne, 1999)*.

2.3.2.1.2. Sampling strategy

Step I: Pre-sampling procedure

There are a few activities required to assure that instruments are working optimally prior to deployment in the field. These activities include: i) factory calibrations, ii) flow calibrations, iii) zero calibrations, iv) leak tests, v) internal filter changes, and vi) general instrument settings check. The above mentioned have to be done as specified by the manufacturer *(Table 2.3)*. The photometric instruments used during the study were sent for yearly calibrations as suggested by the manufacturer. This calibration is done by using a reference photometer (Model 8587) that is gravimetrically calibrated to Arizona Test Dust (ISO 12103-1, A1 Test Dust). The instruments were flow calibrated using the Jar Method *(Figure 2.23)*, which is an Occupation Safety and Health Administration (OSHA) approved method.

This method requires the use of a Calibration Jar, a Dorr-Oliver cyclone, a soap bubble flow meter such as the Gillian Gilibrator II (Sensidyne, St. Petersburg, U.S.A.), as well as the instrument on which the inlet will be used. The cyclones were cleaned with isopropyl alcohol before each calibration and the selected instrument undergoing calibration was switched on prior to calibration to stabilise. The Dorr-Oliver cyclone was placed into the calibration jar with a short piece of tubing connecting the cyclone to the inside of the jar lid. A piece of tubing was then connected from the selected pump to the top of the jar lid. An additional piece of tubing was connected from the second inlet on the jar lid to the flow calibrator. The first few readings on the Gilibrator II calibrator were not used, however, 10 flow readings were recorded with the average being used for flow calibration purposes.

Table 2.3. Recommended maintenance schedule for continuous photometric monitoring instruments *(TSI Incorporated, 2010, 2012a, 2014)*.

Item	**Frequency**		
	DustTrak Model 8520	**DustTrak II Model 8530**	**SidePak AM510**
Perform zero check	Daily (or before long tests)	Daily (or before long tests)	Daily (or before long tests)
Clean 10 µm nozzle, inlet, and sample tube	350 hr. at 1 mg/m3*	350 hr. at 1 mg/m3*	-
Replace internal filter	700 hr. at 1 mg/m3*	350 hr. at 1 mg/m3*	-
Clean cyclone	Before each use	Before each use	Before each use
Factory calibration and cleaning	Annually	Annually	Annually
Flow Calibration	As needed	As needed	As needed

Additionally, the individual cyclone pieces were checked for any indications of damage and deteriorations. Parts that appeared to be damaged or deteriorated were replaced. Leak tests were completed to check the O-ring, tubing and pump by connecting the cyclone to the selected instrument or pump at the selected 1.7 $L.m^{-1}$ flow rate, and then closing the inlet with a finger. The system passed the leak test if the instrument

gave a flow fault error, this is also known as the pump-fault leak test. During the sampling campaigns, the cyclones were regularly cleaned by unscrewing the grit pot from the cyclone and tapping it upside down on a solid surface and rinsing it with isopropyl alcohol *(Occupational Health and Safety Administration, 1999)*.

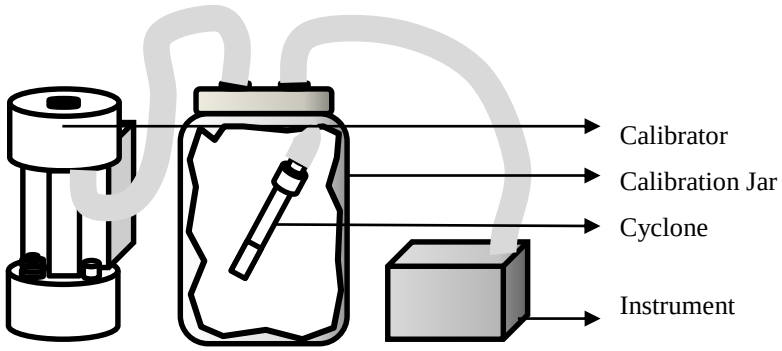


Figure 2.23. A schematic representation of Jar Method calibration of the 10mm Nylon Dorr-Oliver cyclone for the continuous photometric instruments (created by B. Language, 2017).

The zero calibrations were done prior to each sampling event by attaching the zero filter and following the procedure as described in the individual instrument operating manuals. By zeroing the instruments, it allows for higher accuracy at low aerosol concentrations *(TSI Incorporated, 2012a)*. The internal filters of the DustTrak instruments were also changed as need (the SidePak doesn't have an internal filter). The final step was to ensure that the instrument was set to the correct date, time, and five-minute logging interval. The instrument lock-function was used to prevent the accidental switching off of instruments by unwanted touching and tampering.

Step II: Field sampling procedure

The deployment (location and height) of the monitoring instruments within the indoor environment of each household was replicated as close as possible. The ideal was to place the instruments within the kitchen area, however, if this could not be achieved the living room was chosen as the secondary location for the instruments. The instruments were rotated to different houses on a weekly or two-weekly basis depending on the sampling campaign and the number of instruments that were available.

Step III: Data downloading procedure

Data downloading coincided with maintenance and site visits as given in *Table 2.11*. This method provided six (6) sets of raw data, including, i) data from the continuous instruments retrieved as ASCII Text files (.txt) from the instruments using the TrakPro™ versions 3.10 and 4.70 software *(TSI Incorporated, 2019)* and ii) written field logs for the continuous sampling that were scanned and saved as Portable Document

Table 2.4. The number of individual households sampled during continuous monitoring between 2013 and 2017.

Campaign	Year	Settlements	Households (N)				Household ID
			ISFB	NSFB	OSFB	Total	
Summer	2014	KwaDela	7	4	-	**11**	H001, H002, H003, H004, H005, H006, H009, H010, H011, H013, H015, H018, H022
	2015	KwaDela	11	4	-	**15**	H001, H003, H004, H005, H006, H008, H010, H011, H013, H015, H016, H018, H021, H021, H022, H023
	2016	KwaZamokuhle	9	-	-	**9**	H024, H025, H026, H027, H028, H029, H030, H031, H032
		Jouberton	-	8	-	**8**	H147, H151, H155, H160, H173, H177, H185, H191
		Agincourt	2	-	8	**10**	H042, H043, H052, H053, H062, H063, H072, H073, H082, H083
	2017	KwaZamokuhle	1	1	-	**2**	H024, H251
		Jouberton	1	8	-	**9**	H200, H204, H214, H219, H224, H225, H240, H242, H249
		Agincourt	3	2	5	**10**	H095, H096, H105, H106, H115, H117, H125, H126, H135, H138
		Giyani	-	1	7	**8**	H033, H034, H036, H037, H038, H039, H040, H041
Winter	2013	KwaDela	12	4	-	**16**	H001, H002, H003, H004, H005, H007, H008, H009, H010, H011, H013, H014, H015, H016, H018, H019
	2014	KwaDela	12	4	-	**16**	H001, H002, H004, H005, H006, H008, H009, H010, H011, H013, H014, H015, H016, H017, H018, H019, H021, H022
	2015	KwaZamokuhle	1	-	-	**1**	H024
	2016	KwaZamokuhle	9	-	-	**9**	H024, H025, H026, H027, H028, H029, H030, H031, H032
		Jouberton	1	9	-	**10**	H147, H151, H155, H160, H165, H175, H185, H190, H191, H194
		Agincourt	2	-	8	**10**	H042, H043, H052, H053, H062, H063, H072, H073, H082, H083
	2017	KwaZamokuhle	1	1	-	**12**	H024, H251
		Jouberton	1	9	-	**10**	H200, H204, H210, H214, H225, H227, H242, H244, H243, H248
		Agincourt	3	2	5	**10**	H095, H096, H105, H106, H115, H117, H125, H126, H135, H138
		Giyani	-	1	7	**8**	H033, H034, H036, H037, H038, H039, H040, H041
Spring	2016	KwaZamokuhle	9	-	-	**9**	H024, H025, H026, H027, H028, H029, H030, H031, H032
		Giyani	-	1	2	**3**	H033, H034, H035

Format (.pdf) files. The files were stored as 'Level_00 – Raw Data' and were not edited or changed in any manner. Further handling of the data is described in *Section 2.4.3.1*.

2.3.2.1.3. Data collection campaigns

Continuous particulate measurements were taken over all twenty-one (21) sampling campaigns as given in *Table 2.2*. The division of households among ISFB, NSFB, and OSFB is given in *Table 2.4* below.

2.3.2.2. Filter sampling and elemental composition characterisation (Objective III)

The intermittent gravimetric sampling method used is closely modelled on the 1998 National Institute for Occupation Safety and Health (NIOSH) procedure for monitoring respirable particulate matter not otherwise regulated (Method 0600, Issue 3) *(NIOSH, 1998)*.

2.3.2.2.1. Instrumentation

The equipment used for the intermittent filter sampling method are as follows: i) the sampler which includes a PM_4 cyclone and the 37mm cassette containing the 37mm filter medium, ii) the personal sampling pumps set to the required flow rate, iii) flow meters, vi) a microbalance scale with a sensitivity of 1µg, v) microbalance calibration weights, vi) forceps for the handling of filters, and vii) a weighing lab that is environmentally stable.

The 37mm filter mediums used are that of borosilicate glass microfiber (BGM) and mixed cellulose ester (MCE). Two types of PM_4 cyclone inlets were also used during the study, namely, the 10mm Dorr-Oliver Cyclone and the GX Cyclone. The main difference between the two cyclones being the flow rate needed to acquire the 50% 4µm cut-size. The 10mm Dorr-Oliver cyclone requires a 1.7 $L.m^{-1}$, as previously mentioned, while the GX Cyclone necessitates a 2.2 $L.m^{-1}$. *Table 2.5* indicates what combination of filter medium and cyclone inlet was used in each settlement.

Table 2.5. Filter medium, cyclone inlet, and sampling interval combinations used in individual settlements.

		KwaDela	KwaZamokuhle	Jouberton	Agincourt	Giyani
Cyclone Inlets	10mm Dorr-Oliver	√	√	-	-	-
	GX	-	-	√	√	√
Filter Medium	Borosilicate	√	-	-	-	-
	Mixed Cellulose Esther		√	√	√	√
Exposure Time	12-hr	√	√	-	-	-
	24-hr	-	-	√	√	√

2.3.2.2.2. Sampling strategy

Step I: Pre-sampling procedure

The pre-sampling filter preparations are essential and were completed in a clean laboratory setting under controlled conditions with the temperature at 22°C ± 2°C and relative humidity at 60% ± 2%.

Calibration weights, 1g and 20g, were used to calibrate the microbalance prior to each weighing session. These calibrations were recorded in a logbook as to provide traceability. Before each filter weighing session, the balance was zeroed as to reduce the possibility of incorrect mass readings *(Figure 2.24.a)*. It was not necessary to use an external anti-static radiation source as the XP26 DeltaRange Microbalance (Mettler-Toledo AG, Greifensee, CH) has an internal anti-static source.

The descriptive statistics of the one-hundred-and-seventeen (117) weighing session conducted between 2014 and 2017 are summarised in *Table 2.6*. The microbalance showed a 0.001653% and 0.00024% difference for the 1g and 20g calibration weights, respectively.

Table 2.6. Descriptive statistics for the microbalance weight calibration for daily weighing sessions.

Calibration Weight		**1g**	**20g**
No. of Sessions		117	117
Mean		1.000016	20.00005
±SD		0.000003	0.00002
Std. Err.		<0.000001	<0.00001
Min		1.000009	20.00002
%	**25th**	1.000016	20.00003
	Median	1.000016	20.00004
	75th	1.000018	20.00006
Max		1.000022	20.00009

Note: ±SD = standard deviation of mean**; Std. Err.** = Standard error of the mean

The filters were inspected for any imperfections and equilibrated for approximately twenty-four (24) hours before weighing commenced. Each filter was weighed three (3) times and the masses recorded in a logbook after which it was captured electronically. The filter was then placed in a petri-slide containing a unique reference, usually designated by *Settlement-Year-Season-Size Fraction-Filter Number*. The petri-slides were then transferred to the fume-hood. Here the 37mm cassettes, consisting of three parts, were loaded with the weighed filters and sealed with caps at the inlet and outlet ends *(Figure 2.24.b)*.

Thirty-seven-millimetre shrink seals were used to prevent the infiltration of contaminated air into the cassette while handling took place. The loaded cassette was marked with the same unique reference as the

petri-slide. The loaded cassettes were sealed in containers to prevent contamination during transportation between the laboratory and field *(Figure 2.24.c)*.

a) Microbalance

b) Loaded filter cassettes

c) Sealed filter cassettes

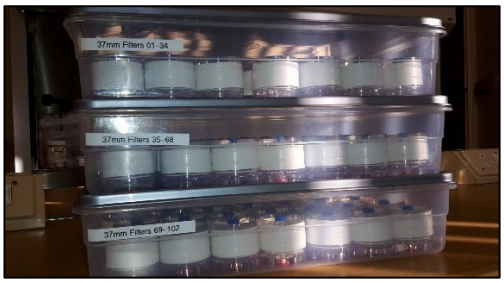


Figure 2.24. Photo of a) the XP26 DeltaRange Microbalance used for filter weighing, b) assembled 37mm cassettes, and c) sealed containers used for transporting 37mm cassettes between the field and laboratory environments (photos taken by B. Language, 2015).

Step II: Field sampling procedure

The cyclones and 37mm cassettes were set up as seen in *Figure 2.25 a and b*. Prior to the commencement of the field sampling campaigns, the personal sampling pumps were calibrated using the Gillian Gilibrator II calibration systems, as described previously, by making use of the Jar Method.

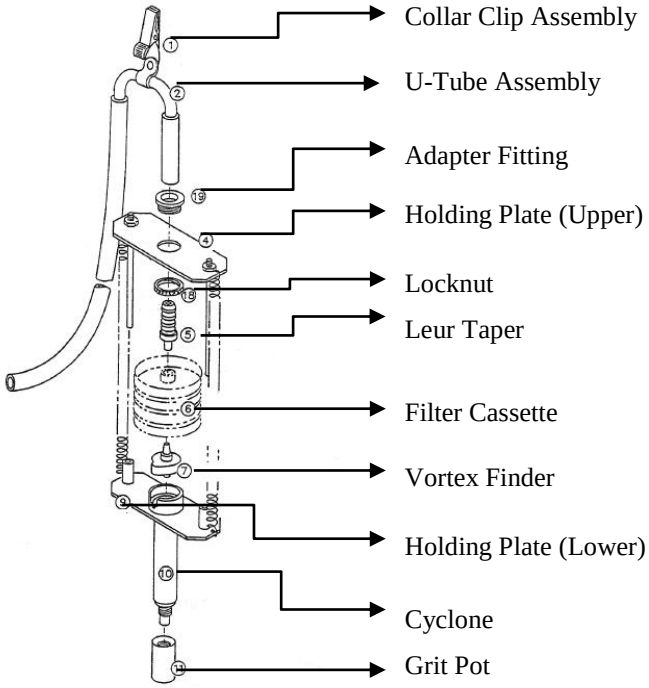
The pumps were calibrated to a flow of 1.7 $L.m^{-1}$ ± 5% and 2.2 $L.m^{-1}$ ± 5% (depending on the cyclone used), while connected to a 37mm filter cassette, as to obtain the 50% 4µm cut size associated with the cyclones.

A filter cassette was removed from the sealed container. The unique reference was recorded on the appropriate sampling log. The caps were then removed from the cassette after which it was placed into the sampling line. The sampling heads were assembled to make sure that the alignment of the filter cassettes and cyclones were not obstructed or misaligned as to prevent leakages. Inlets were fixed to a height of ~1.6m, which is representative of an approximate breathing height. Twelve- and 24-hour sampling intervals were used during this study as indicated in *Table 2.5* above. The 12-hour sampling was conducted from 06:00 to 18:00 and then again from 18:00 to 06:00. The 24-hour sampling did not have a specific start time. The main reasons for this was that the households were not necessarily located close to each other or

available at specific times. However, times were arranged with individual households to keep the sampling period as close to 24-hours as possible.

After each sampling event, the 37mm cassettes were removed from the sampling head and the caps were placed back on the inlet and outlet ports of the cassettes. Attention was also focused on not inverting the cyclone as this could deposit the larger non-respirable particles that have accumulated in the grit pot onto the filters. The cassettes that were exposed were then stored in a sealed container to prevent any additional and unwanted particulate matter accumulating on the filter. The sealed containers were then transported back to the laboratory for post-sampling analysis.

a) Exploded view of assembled cyclone



b) Assembled cyclone

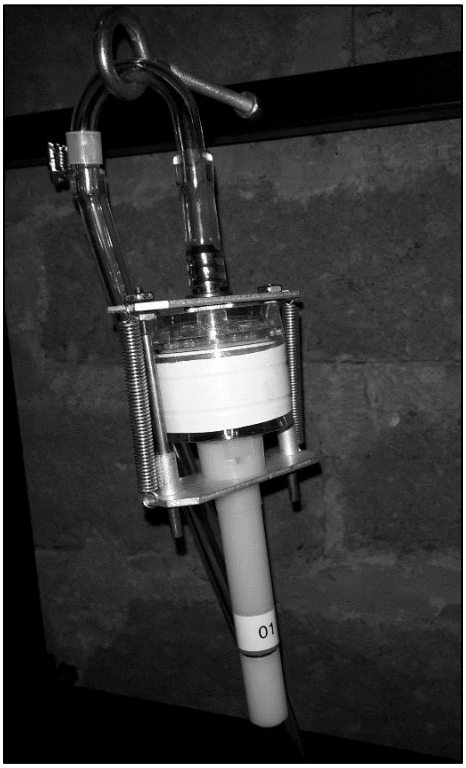


Figure 2.25. A schematic representation of a) the 10mm Nylon Dorr-Oliver cyclone and cassette holder assembly *(Sensidyne, 2003)* and b) an assembled cyclone used during field sampling (photograph by B. Language, 2015).

Step III: Post-sampling procedure

In the weighing lab, the filters were offloaded under a fume-hood and placed in the petri-slide containing the same unique reference. The filters were left to equilibrate after which they were weighed using the same procedure as that of the pre-sampling weighing of the filters *(Figure 2.26.b)*. If the filter was damaged in any way it was noted and excluded from the analysis. The weighed filters were individually stored in petri-slides until further analysis could take place.

a) Exposed vs non-exposed **b) Filter weighing**

Figure 2.26. Photos showing a) a comparison between non-exposed (blue caps) and exposed (red caps) filters, and b) post-exposure filter weighing (photos taken by B. Language, 2015).

Step IV: *Wavelength Dispersive X-Ray Fluorescence*

The filter samples were subject to wavelength-dispersive x-ray fluorescence (WD-XRF) analysis. This analysis provides additional information on the mass and elemental composition of the collected respirable particulate matter samples.

A PANalytical Axios^{maX} wavelength dispersive x-ray fluorescence spectrometer was used to identify the elements present in the individual filter samples. The spectrometer implements a sequential analysis method, thus it only analyses a single element at a time. The spectrometer was equipped with a rhodium tube and a 4 kW generator. A 20mm collimator mask was selected, thus an area with a 20mm diameter was analysed. The instrument used helium as a sampling medium in the analysis chamber. There were two available detectors, namely the flow- and scintillation detectors. The parameters selected to analyse individual elements have been optimised as to obtain maximum intensity.

The elements included in the WD-XRF analysis were Na, Mg, Al, Si, P , S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu ,Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Pd, Ag, Cd, In, Sn, Sb, I, Ba, Ce, W, Pt, Au, Hg, Tl, Pb, and Bi. These elements range from metals to metalloids and included non-metallic elements, however, most lanthanoids, actinoids and noble gasses were excluded from the analysis.

MICROMATTER^{TM} calibration standards were used for calibration purposes. These standards are National Institute of Standards and Technology (NIST) traceable reference materials and have a Nucleopore ® polycarbonate aerosols membrane backing mounted in a 25mm ring mount. Each element had two calibration points that were obtained from a very light standard ranging between 3-8 µg.cm^{-2} and a heavier standard ranging between 40-60 µg.cm^{-2}.

A summary of the elements and calibration standards used for the filter application is given in *Table 2.7*. The limit of detection (LOD) and limit of quantification (LOQ), given in *Table 2.7*.

The filter samples were placed in the 37mm sample cup holders *(Figure 2.27)*. Filters were kept in place by making use of Teflon filter holders which consist of three parts, namely the i) filter holder bottom; ii) filter holder top; and iii) the filter support. The cups were placed on the trays and loaded into the spectrometer. Using the SuperQ software *(Malvern PANalytical Ltd, 2010)*, the measurement queue was created for the 56 available positions. Each filter was analysed for an average of 1294 seconds (~22 minutes), while an additional 10 seconds were needed as a medium flush time and an added 2 seconds as delay time between measurement samples.

The laboratory and field logs were scanned and saved as Portable Document Format (.pdf) files. Data were and stored as 'Level_00 – Raw Data' and was not edited or changed in any manner. Further handling of the data is described in *Section 2.4.3.2*.

Table 2.7. Elements included in the WD-XRF analysis and the associated MICROMATTER™ - XRF Standards.

Element	Metals					Metalloids	Non-metals	Description	(µg.cm^{-2}) +/- 5%			
	A	AE	PT	T	L				H	VL	*LOD	*LOQ
Na	√							Sodium or Chlorine as NaCl	519	7.5	0.01	0.04
Mg		√						Magnesium as MgF2	51.8	6.6	0.03	0.10
Al			√					Aluminium as Al metal	53.1	7.1	0.26	0.06
Si						√		Silicon as SiO	58.5	5.3	0.05	0.12
P							√	*Gallium or Phosphorus as GaP ; Ga=31.5 & 3.1 P=11.8 & 3.8	43.3	6.9	0.14	0.04
S							√	Sulphur as CuSx Cu=31.9 S=10.5 and as InSx In=5.6 S=1.4	42.4	7.0	0.08	0.10
Cl							√	Chlorine as KCl	47.9	7.3	0.13	0.78
K	√							Potassium or Chlorine as KCl	46.4	7.2	0.16	0.15
Ca		√						Calcium as CaF2	45.4	6.8	0.15	0.43
Ti				√				Titanium as Ti metal	51.8	6.6	0.55	0.24
V				√				**Vanadium as V metal	38.3	7.8	0.27	0.39
Cr				√				Chromium as Cr metal	39.0	6.0	0.34	0.48
Mn				√				**Manganese as Mn metal	54.8	6.3	0.39	0.44
Fe				√				**Iron as Fe metal	46.1	6.7	0.03	1.65
Co				√				Cobalt as Co metal	46.5	4.8	1.07	0.82
Ni				√				Nickel as Ni metal	50.3	7.1	0.41	1.03
Cu				√				Copper as Cu metal	48.9	6.0	0.02	1.19
Zn				√				*Zinc as ZnTe	53.2	7.1	0.02	0.10
Ga			√					*Gallium or Phosphorous as GaP; Ga=41.0 & 4.2 P=9.4 & 4.4	50.4	78.6	0.02	3.26
Ge						√		Germanium as Ge metal	49.4	6.3	0.03	1.25

Table 2.7. (Continued)

Element	Metals					Metalloids	Non-metals	Description	(µg.cm^{-2}) +/- 5%			
	A	AE	PT	T	L				H	VL	*LOD	*LOQ
As						√		*Arsenic or Gallium as GaAs; Ga=19.2 & 3.0 As=30.8 & 4.0	50.0	7.0	1.08	0.07
Se							√	Selenium as Se metal	46.8	4.5	0.02	0.06
Br							√	Bromine or Cesium as CsBr	46.6	6.5	0.02	0.06
Rb	√							Rubidium or Iodine as RbI	42.8	7.0	1.76	0.08
Sr		√						Strontium as SrF_2	50.9	5.9	0.03	3.26
Y				√				Yttrium as YF_3	51.8	5.27	7.18	0.07
Zr				√				Zirconium as ZrF_4	59.2	4.17	0.00	0.06
Nb				√				Niobium as Nb_2O_3	50.1	6.6	0.27	5.33
Mo				√				Molybdenum as MoO_3	59.8	6.8	0.01	0.10
Pd				√				Palladium as Pd metal	52.1	6.1	0.03	21.75
Ag				√				**Silver as Ag metal	52.3	7.0	0.26	0.00
Cd				√				*Cadmium as CdSe	53.0	5.72	0.05	0.82
In			√					Indium as In metal	52.6	6.0	0.04	0.13
Sn			√					Tin as Sn metal	55.5	5.3	0.06	0.20
Sb						√		Antimony as Sb metal	53.5	6.7	0.05	0.15
I							√	Iodine or Rubium as RbI	54.0		0.16	0.50
Cs	√							Bromine or Cesium as CsBr	46.6	6.5		
Ba		√						Barium as BaF2	48.9	6.5	0.10	0.30
Ce					√			Cerium as CeF3	51.0	7.23	0.59	1.80
W				√				Tungsten as WO_3	47.9	6.4	0.28	0.84
Pt				√				Platinum as Pt Metal	51.3	6.0	0.40	1.23
Au				√				Gold as Au metal	48.6	4.7	0.39	1.17
Hg				√				Mercury as AgHg; Ag=28.5 Hg=27.5 and *HgTe; Hg=3.7 Te=2.5	56.0	6.2	0.40	1.22
Tl			√					Thallium as TlCl	45.1	5.9	0.38	1.14
Pb			√					**Lead as Pb metal	52.3	7.1	0.55	1.67
Bi			√					Bismuth as Bi metal	51.6	7.7	0.56	1.68

A- Alkali; **AE** – Alkali Earth; **PT** –Post Transition; **T** – Transition; **L** - Lanthanoids* may not be stoichiometric; ** will oxidize; **H** – Heavy Standard; **VL** – Very Light Standard; **LOD** – Limit of Detection; **LOQ** – Limit of Quantification

Step V: Data downloading procedure

This method provided four (4) sets of raw data, including, ii) personal sampling pump data retrieved as Comma Separated (.csv) files using the Gilian Connect™ software *(Sensidyne, 2019)*; ii) elemental data

retrieved as a comma separated file (.csv) from the SuperQ software *(Malvern PANalytical Ltd, 2010)*; iii) written laboratory logs of the recorded filter masses; and iv) written field log for the gravimetric sampling.

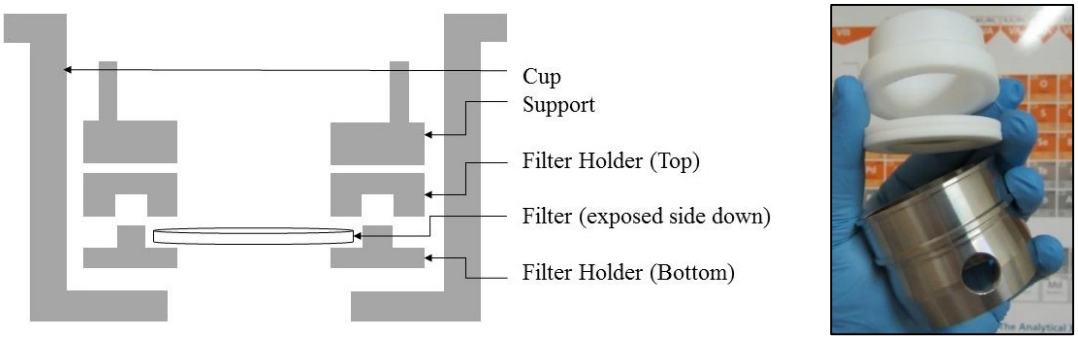


Figure 2.27. Schematic depicting the filter holder designed for use in a 37mm cup (photograph taken by B. Language, 2016).

2.3.2.2.3. Data collection campaigns

The intermittent filter sampling was conducted in sixteen (16) of the twenty-one (21) sampling campaigns *(see Table 2.2)*. This included KwaDela (4), KwaZamokuhle (5, 7, 9, and 10), Jouberton (11, 12, 13, and 14), Agincourt (15, 16, 17, 18, and 19), and Giyani (19, 20, and 21). Thus, it included eight (8) summer, seven (7) winter, and one (1) spring sampling period(s). Thus, it excludes campaigns 1, 2, 3, 6, and 8. The households were classified as discussed in *Section 2.3.1*.

Table 2.8. Breakdown of the number of individual households used during intermittent filter sampling in each settlement between 2015 and 2017.

Season	Year	Highveld Region									Lowveld Region					
		KwaDela			KwaZamokuhle			Jouberton			Agincourt			Giyani		
		ISFB	NSFB	OSFB	ISFB	NSFB	OSFB	ISFB	NSFB	OSFB	ISFB	NSFB	OSFB	ISFB	NSFB	OSFB
Summer	2015	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2016	-	-	-	4	-	-	-	46	4	6	4	40	-	-	-
	2017	-	-	-	1	1	-	-	44	6	9	6	35	-	1	7
Winter	2015	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
	2016	-	-	-	-	-	-	-	46	4	6	4	40	-	-	-
	2017	-	-	-	1	1	-	-	44	6	9	6	35	-	1	7
Spring	2016	-	-	-	-	-	-	-	-	-	-	-	-	-	1	2

- No samples collected

A total of two-hundred-and-eleven (211) and two-hundred-and-eighteen (218) households were sampled for both summer and winter, respectively, and three (3) were sampled during the transitioning spring period. Twenty-seven (27) of the houses sampled during summer were ISFB; hundred-and-two (102) were NSFB,

and eighty-two (82) were OSFB. The breakdown is similar for winter, as there were thirty-four (34) ISFB; hundred-and-two (102); and eighty-two (82) OSFB households. The spring period included a single (1) NSFB and two (2) OSFB houses. The above is further categorised by settlement in *Table 2.8*.

2.3.2.3. Collocated sampling technique (Objective I)

The collocated sampling technique is where various instruments and sampling methods were set-up next to each other in the same environment. The main purpose of this was to i) calculate calibration factors for the correction of any over- or underestimation by the photometric instruments; ii) identify whether it is possible to compare data from different models of photometric instruments; and iii) identify convention factors for calculating PM_{10} and $PM_{2.5}$ from existing PM_4 measurements to enable comparisons with existing guidelines and standards.

2.3.2.3.1. Instrumentation

Due to the nature of the indoor environment in which the sampling took place, it was necessary to devise a comprehensive and easily deployable sampling strategy with minimal impact on the residents of the house. A sampling table was designed and manufactured to service the needs associated with the collocated sampling experiments *(Figure 2.28)*. The simplified layout of the sampling tables, designed specifically for the collocated continuous and gravimetric sampling, can be viewed in *Figure 2.29*. The sampling table can be divided into different sections, namely, i) power supplies; ii) switch control; iii) logger; iv) flow meters; v) voltage meter; vi) plugs, and vii) power distribution board.

Figure 2.28. Setup of the gravimetric sampling within the indoor environment of the households (photograph by B. Language, 2015).

The main power supplied (230V, 50Hz) to the table comes from the wall socket or distribution board within the house. The 230V power flows directly to the plugs which are used to supply power to the individual instruments, the voltage meter, and the power supplies. Power outages are a common occurrence in the field. It is important to know when these outages occur and the specific duration as the time sampled is a significant contributing factor in the gravimetric samples. The voltage meter is specifically incorporated for this purpose. The voltage meter has a built-in converter to drop the 230V input to 1V, this is due to the Campbell Scientific CR200 logger only excepting an input up to 2.5V. Eight power supplies are utilised in the sampling table, four of which are the primary power supplies and four secondary power supplies used as a back-up should one of the primary power supplies fail. The main purpose of these units is to convert the 230V input to lower voltages needed by the logger and flow meters. The logger requires an input of 12V while the flow meters need only 5V in order to be operational.

The wiring and voltage conversion for the voltage meter and individual powers supplies can be viewed in *Figure 2.30.a*. The flow meters had a voltage output of 4.5V. Similar to the voltage meter, the output voltage for the flow meters had to be lowered to the acceptable 2.5V input of the logger. Resistors were used for this purpose. The logger was supplied with an additional 12V back-up battery, to avoid interference from expected power outages. The wiring connections for the logger is represented in *Figure 2.30.b*.

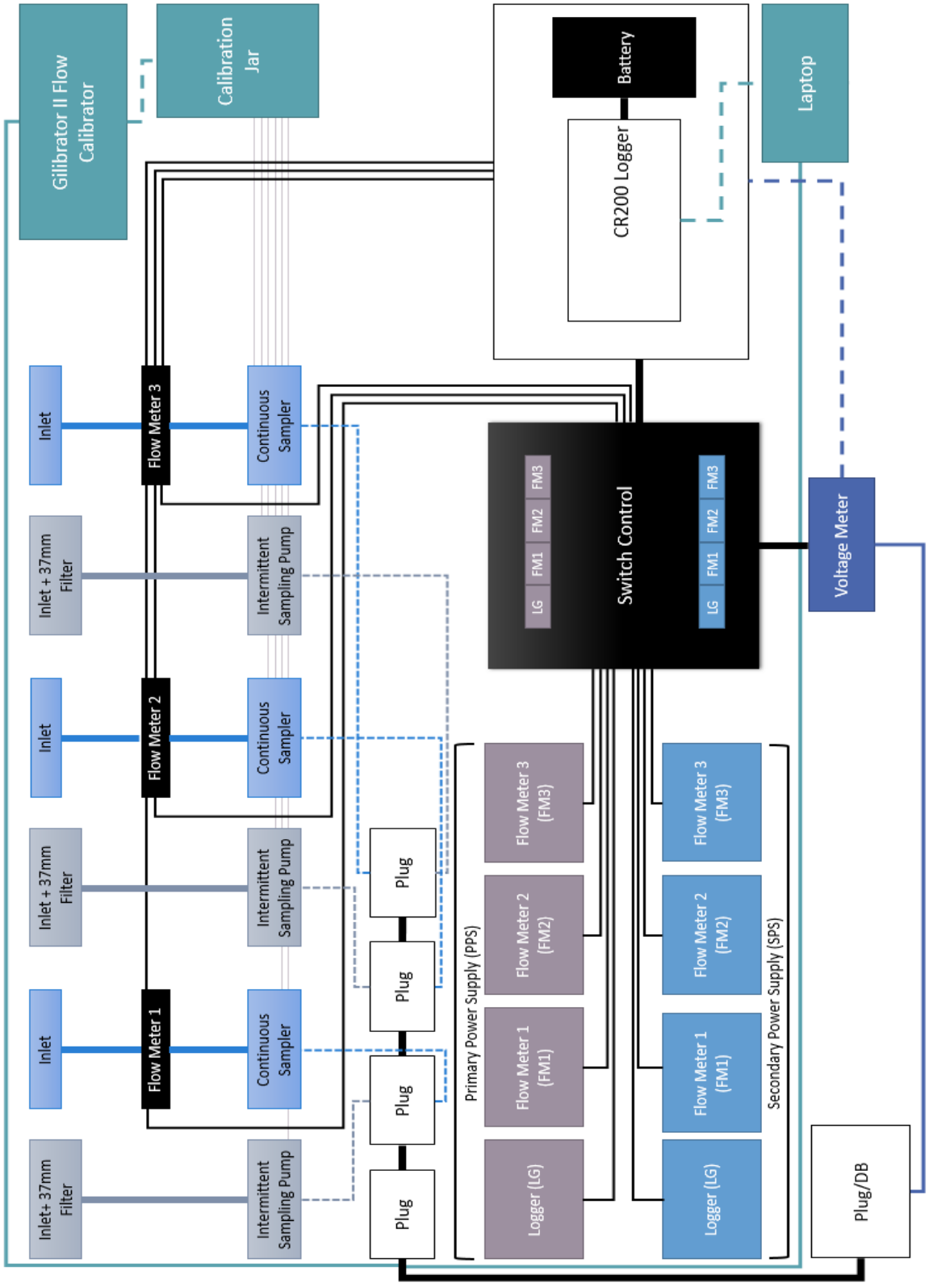
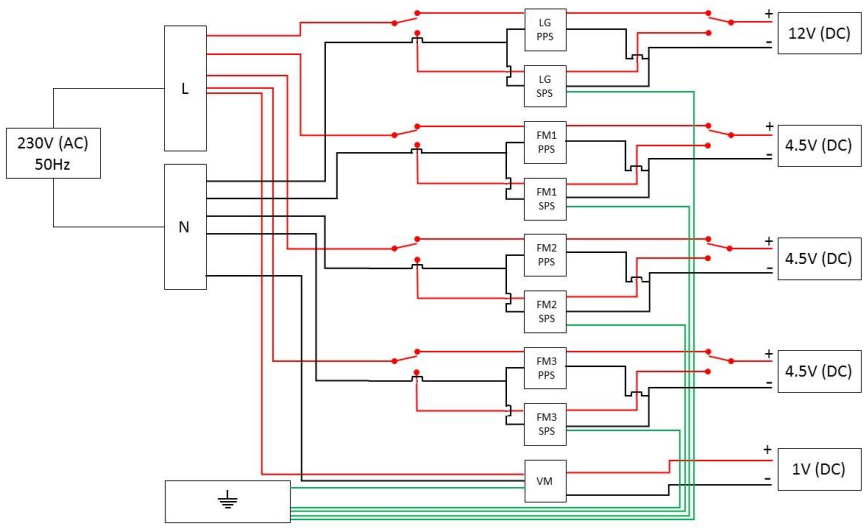
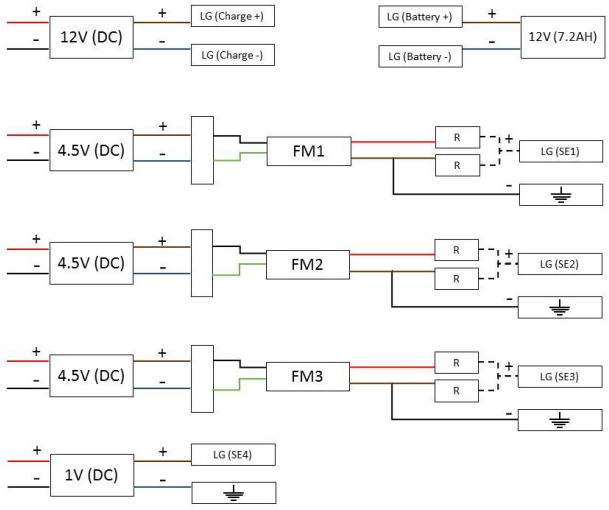


Figure 2.29. A simplified schematic drawing of the collocated gravimetric sampling table.

a)



b)



AC - Alternating Current
AH - Amp Hour
L - Live
DB - Distribution Board
DC - Direct Current
FM - Flowmeter
Hz - Hertz
LG - Logger
N - Neutral
PPS - Primary Power Supply
SPS - Secondary Power Supply
V - Volts
VM - Voltage Meter

Figure 2.30. Images indicating the electrical wiring of the collocated sampling table, with a) showing the input of 230V (50Hz) and conversion to usable voltages for both the logger (12V) and flow meters (4.5V) for both the primary- and secondary power supplies; and b) the wiring of the flow meters, battery, and voltage meter to the logger.

2.3.2.3.2. Sampling strategy

Step I: Pre-sampling procedure

The preparation prior to deployment is exactly as described from Method I and Method II in *Sections 2.3.2.1.2* and *0*, respectively.

Step II: Field sampling procedure

Based on the purpose of the evaluation study, varying photometric instrument and particulate size fraction inlets were used, see *Table 2.9*.

The evaluation studies comprised of i) a comparison between continuous instruments and the intermittent gravimetric sampling; ii) a comparison between the DustTrak (DT), DustTrak II (DT II), and SidePak (SP) continuous photometric instruments; and iii) a comparison between different size fractions measured with the same model photometric instrument.

Table 2.9. Photometric instruments and size fractions used during field collocated evaluation experiments.

Evaluation Study No.	Description of collocated comparison	Photometric Instrument			Intermittent Gravimetric Sampling	Size Fraction			
		DT	DT II	SP		PM_1	$PM_{2.5}$	PM_4	PM_{10}
1	Gravimetric vs. Continues	√	√	√	√			√	
2	Continuous vs Continuous	√	√	√				√	
3	Continuous Size Fraction			√		√	√	√	√

Step III: Post-sampling procedure

The post-sampling procedure is exactly as described for Method I and Method II in *Section 2.3.2.1.2* and *0*, respectively.

Step IV: Data downloading procedure

This method provided six (6) sets of raw data, including, i) data from the continuous instruments retrieved as ASCII Text files (.txt) from the instruments using the TrakPro™ versions 3.10 and 4.70 software *(TSI Incorporated, 2019)*; ii) CR200 logger data retrieved as Comma Separated (.csv) files using the LoggerNet™ version 4.x software *(Campbell Scientific Inc., 2017)*; iii) personal sampling pump data retrieved as Comma Separated (.csv) files using the Gilian Connect™ software *(Sensidyne, 2019)*; iv) written laboratory logs of the recorded filter masses; and written field log for the v) continuous and vi) gravimetric sampling. The laboratory and field logs were scanned and saved as Portable Document Format (.pdf) files. The files were stored as 'Level_00 – Raw Data' and were not edited or changed in any manner. Further handling of the data is described in *Section 2.4.2*.

2.3.2.3.3. Data collection campaigns

The collocated evaluation studies were nested within the twenty-one (21) main sampling campaigns conducted during spring, summer, and winter periods across the five residential settlements. The sampling was not done in all the households sampled in each individual settlement, but rather in a sub-set of houses. The individual households utilised for the field evaluation of the photometric instruments are indicated in *Table 2.10.* The households were classified as discussed in *Section 2.3.1*.

Photometric calibration factors

The collocation evaluation study for the photometric calibration factors was conducted in sixteen (16) of the twenty-one (21) sampling campaigns *(see Table 2.2)*. Same as described in *Section 2.3.2.2.3*.

The households that were sampled during each campaign are given in *Table 2.10*. A total of fifty-eight (58) households were sampled for summer and fourth eight (48) winter, respectively, and three (3) households were sampled during the transitioning spring period. Nineteen (19) of the fifty-two (52) houses sampled during summer were ISFB; seventeen (17) were NSFB, and sixteen (16) were OSFB.

The breakdown is similar for winter, as there were eleven (11) ISFB; twenty (20) NSFB; and seventeen (17) OSFB households. The spring period included a single (1) NSFB, ISFB, and OSFB house.

Table 2.10. Individual households used during collocated field evaluations of photometric instruments between 2015 and 2017.

Campaign	Year	Dates (DD/MM)	Settlements	Households
Summer	2015	26/03 – 13/04	KwaDela	H01, H05, H13, H18
	2016	22/02 – 07/03	KwaZamokuhle	*H24
		14/04 – 20/05	Jouberton	H151, H155, H160, H177, H185
			Agincourt	H042, H043, H052, H053, H062, H063, H072, H073, H082, H083
	2017	01/11 – 20/11	KwaZamokuhle	H24, H251
		01/02 – 09/03	Jouberton	H200, H204, H214, H219, H224, H225, H240, H242, H249
		01/02 – 09/03	Agincourt	H095, H096, H105, H106, H115, H117, H125, H126, H135, H138
		06/02 – 08/03	Giyani	H033,H034, H036, H037
Winter	2015	07/07 – 21/07	KwaZamokuhle	*H24
	2016	14/07 – 18/08	Jouberton	H147, H151, H155, H160, H165, H175, 185, H190, H191, H194
			Agincourt	H042, H043, H052, H053, H062, H063, H072, H073, H082, H083
	2017	26/07 – 16/08	KwaZamokuhle	H24; H251
		01/06 – 06/07	Jouberton	H210, H214, H225, H227, H242, H243, H244, H248
			Agincourt	H095, H096, H105, H106, H115, H117, H125, H126, H135, H138
		03/07 – 31/07	Giyani	H033, H036, H037, H038, H039
Spring	2016	06/09 – 15/09	Giyani	H033, H034, **H035

*** Instrument comparison; ** Size fraction comparison**

Instrument comparison

This sampling was conducted in a single household (H024) located in KwaZamokuhle *(Figure 2.31)*. The evaluation consisted of two (2) sampling periods nested within campaigns 5, and 7 *(see Table 2.2)*.

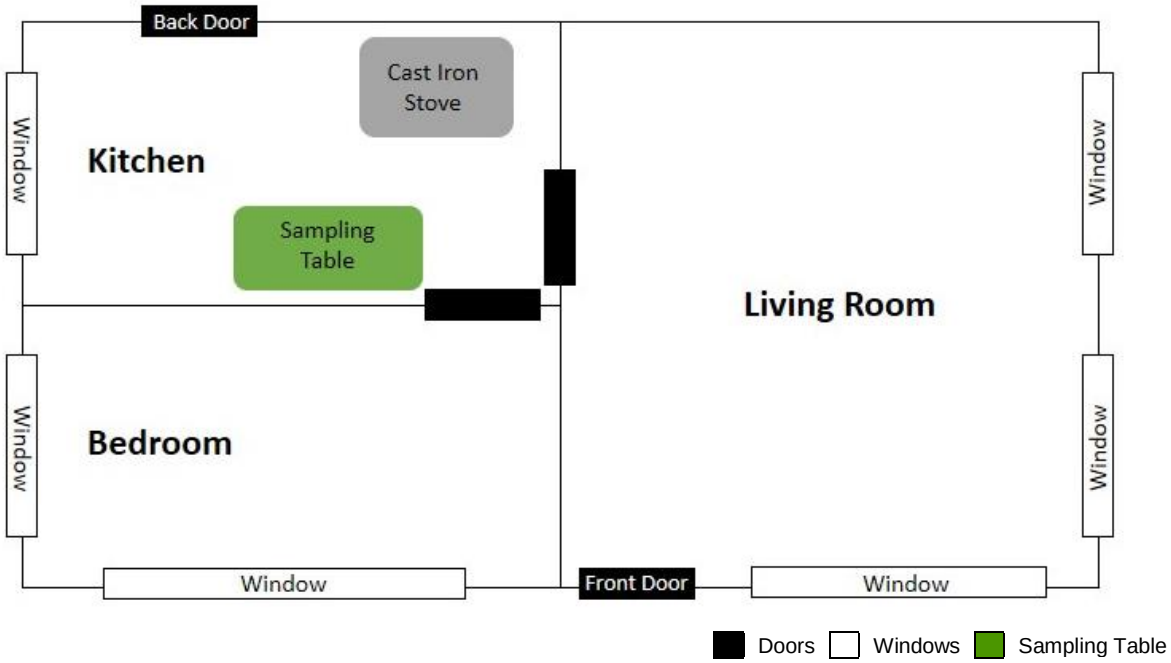


Figure 2.31 Typical layout of the RDP households and the location of the sampling table in KwaZamokuhle for H24.

These were performed in KwaZamokuhle during winter 2015 (7 July to 21 July) and summer 2016 (22 February to 7 March). The household is considered to be a typical RDP structure with three to four rooms, namely a kitchen, one or two bedrooms, and a living area. The household is classified as ISFB as indoor coal combustion is used as an energy source for both heating and cooking activities. The combustion activities take place within a typical cast iron coal stove in the kitchen area. This is especially true during the cold winter months.

Size fraction comparison

The sampling was conducted in a single household (H035) in Giyani during sampling campaign 19 *(see Table 2.2)* in spring 2016. Monitoring took place over four consecutive days and commenced at 11h50 on 6 September and ended at 08h50 on 9 September *(Table 2.10)*. It is a traditional dwelling of approximately 30 years old with two permanent occupants. The dwelling does have an indoor kitchen area, however, they use an outside fireplace (known as a Segôtlô) on a daily basis for cooking *(Figure 2.32)*. Wood is mainly used for this purpose. The house had signs of dampness, mould, and leaks. During periods of hot weather, the residents describe the house as cooler inside than outside and mainly use open windows and doors for ventilation.

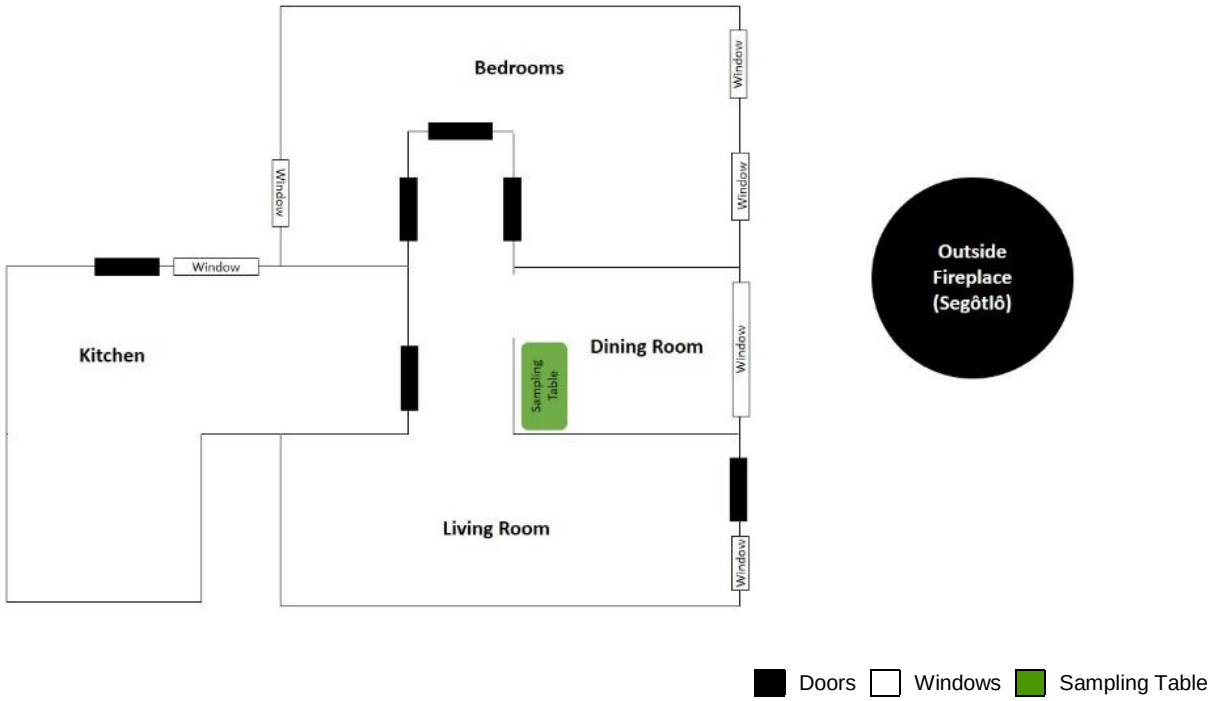


Figure 2.32 Structure of H035 in Ka-Dizingidzingi village within Giyani and the location of the sampling conducted in the house.

2.3.2.4. Maintenance and site visits

An integral part of the fieldwork was to conduct site visits on a weekly or bi-weekly basis, depending on the requirements of the individual research projects. The main purpose of these site visits was for data downloading, instrument maintenance, and instrument relocation activities. The site visits conducted for each sampling campaign, including the date of instrument deployment and decommissioning, are summarised in *Table 2.11*.

In spite of the frequent visits to the sites, numerous instruments failures were experienced. These instrument failures were caused by issues such as power failures, ageing instrumentation, and households switching off the instrument during the evening due to the perceived noisiness of the pumps.

Table 2.11 Summary of site visits conducted for each sampling campaign.

Campaign	Site visit no.												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
KwaDela													
Winter 2013	July						August				September		
	*2	10	17	24	27	31	6	13	21	28	4	13	**27
Summer 2014	February			March				April					May
	*10	19	26	5	12	18	25	1	8	15	22	29	**6
Winter 2014	July				August				September				
	*10	16	22	29	4	11	19	26	2	9	**18		
Summer 2015	February			March				April					
	*11	16	23	2	9	16	***26***	****13***					
KwaZamokuhle													
Winter 2015	July												
	7	****21***											
Spring 2015	September		October		November								
	*2	17	15	27	2	13	18	**26					
Summer 2016	February		March			April							
	*24	29	07	18	24	1	8	**19					
Winter 2016	July		August		September								
	*12	26	9	23	**09								
Winter 2017	July	August											
	*26	2	9	**16									
Summer 2017	November												
	*1	8	15	**20									
Giyani													
Spring 2016	September												
	*6	***7***	***9***	**15									
Summer 2017	February			March									
	*6	14	22	1	**8								
Winter 2017	July												
	*3	10	17	24	**31								
Agincourt & Jouberton													
Summer 2016	April			May									
	*14	21	28	6	12	**20							
Winter 2016	July			August									
	*14	21	27	4	10	**18							
Summer 2017	February				March								
	*1	9	15	23	1	**9							
Winter 2017	June					July							
	*1	08	14	22	28	**6							

Intensive indoor sampling campaigns: ***** Date of deployment; ****** Date of decommissioning

2.3.2.5. Secondary data collection

2.3.2.5.1. South Africa Census

A national census is conducted every ten (10) years by Statistics South Africa. The most recent census was completed in 2011. It provides population and household statistics at various levels known as enumeration areas (EAs). Different variables were extracted based on the requirement set for the characterisation of the study area *(see Section 2.2)*. The independent variables considered for describing the broader study area include the primary fuels used *(see Section 2.4.1.1)* and various demographic and socio-economic aspects *(see Section 0)*.

2.3.2.5.2. Meteorology (Objective IV)

Consideration is given to the local synoptics and meteorology as well as the overall climatic conditions for each of the five settlement in the study area. The data sets were acquired in the following manner:

Step I: Data identification

Three data sets were identified as relevant to the study, namely i) synoptic weather charts 2013 to 2017; ii) meteorological data for the period 2013 to 2017; and iii) meteorological data for the climatic period of 1981 to 2010. The daily historic synoptic charts were freely available on the South African Weather Service (SAWS) website portal and did not require a special request. Ambient monitoring stations (AMS) situated in close proximity to the settlements were identified *(Table 2.12)*.

Table 2.12. Ambient monitoring stations utilised for describing local meteorological and climatic conditions for individual settlement.

Settlement	AMS No.	AMS Name	Latitude	Longitude	Height	Distance	Years
KwaDela	1**	KwaDela	-26°27'48"	29°39'48	1700	#	2013-2015
	3	Bethal	-26°26'60"	29°26'60"	1650	~22 (W)	1989-2010
KwaZamokuhle	2**	KwaZamokuhle	-26°08'18"	29°44'20"	1677	#	2015-2016
	3	Bethal	-26°26'60"	29°26'60"	1650	~44 (SW)	1989-2010
Jouberton	4	Klerksdorp	-26°53'60"	26°37'12"	1329	~2 (SE)	1992-2010
							2016-2017
Agincourt	5	Phalaborwa Airport	-23°56'24"	31°08'60"	432	~80 (N)	1981-2010
	6	Kruger	-25°23'24"	31°05'60"	865	~55 (SW)	2016-2017
Giyani	7	Thohoyandou	-23°05'24"	30°22'48"	614	~40 (NW)	1983-2010
	8	Giyani	-23°18'60"	30°40'60"	455	*	2016-2017

Note:
South Latitude; East Longitude; Height in m.a.m.s.l; Distance in kilometre and (direction) from settlement;
 # AMS located inside settlement; **C.R.G. monitoring station

Five (5) stations were identified for meteorological data and included AMS-1, -2, -4, -6, and -8. There were only four (4) stations identified for the climatic data, namely AMS-3, -4, -5, and -7. There is a variation in the AMS used for short-term and long term meteorological data as a number of the long-term stations have been decommissioned or there was not sufficient data for the more recent period ranging from 2013 to 2017.

Step II: Data request

The data use and disclosure agreement request form was completed and submitted for approval. The data was received upon approval of the request.

Step III: Data received

The daily synoptic weather charts and monthly climate statistics were received from SAWS as Portable Document Format (.pdf) files. The hourly meteorological observational data, for the period 2013 to 2017, was received as a Microsoft Excel Worksheet (.xls) file. The files were stored as 'Level_00 – Raw Data' and were not edited or changed in any manner. Further handling of the data is described in *Section 2.4.1.3 and 2.4.4*.

2.3.2.5.3. Household questionnaire surveys

The household survey data used in this study were sourced as secondary data from individual research projects. The questionnaire surveys were conducted by trained field workers from the NOVA Institute, NICD, and MRC respectively. The surveys differ based on the needs of the individual project, however, the information collected focused on aspects such as household identification and selection, demographics and socioeconomic status, household member information, household information, environmental services and practices, housing infrastructure, indoor environmental conditions, personal and domestic hygiene, health status, past medical history, and population movement. The data sets were acquired in the following manner:

Step I: Data identification and requests

The specific questionnaires implemented in the respective surveys were requested from the individual project leaders. The main categories of interest were identified based on the questionnaires received. The data use and confidentiality agreement request forms were completed and submitted for approval. The data was received upon approval of the request.

Step II: Data received

The data for KwaDela and KwaZamokuhle were received from the NOVA institute as Comma Separated (.csv) files. The NICD provided data for Jouberton and Agincourt in a Microsoft Excel Worksheet (.xlsx) format. Similarly, the MRC made the data for Giyani available in *.xlsx* format. The above mentioned also included the specific questions asked, relevant codebooks, and metadata. The files were stored as 'Level_00 – Raw Data' and were not edited or changed in any manner. Further handling of the data is described in *Section 2.4.3.3*.

2.3.3. Sampling errors, uncertainties and assumptions

Errors and uncertainties are an inherent part of any experimental procedure. It must, therefore, be taken into account when interpreting data obtained from the use of specific data collection and analysis methodologies. These methodological errors are classified as either random or systematic. Random errors are typically related to the limitations (precision) associated with the specific measurement methods and instrumentation. These errors can fluctuate in either direction and can be identified through statistical analysis. Systematic errors are inaccuracies (bias) in the data that are consistent and reproducible, however, it is often difficult to identify and deal with. Systematic errors cannot be reduced by increasing the number of observations whereas this is possible for random errors. There are numerous factors that can lead to measurement errors caused by natural-, instrument-, or human factors. The most significant random- and systematic errors within the current study are identified and discussed in further detail below.

2.3.3.1. Random errors

The random errors identified during this study are related to uncertainties in measurement methods and instrument resolutions. The errors and associated minimization of uncertainties are discussed below.

2.3.3.1.1. Measurement method

Filter mass concentrations measured by the microbalance

Uncertainties associated with the precision of filter masses recorded for the intermittent filter sampling (Method II) could result from the electronic scale itself, environmental factors associated with the weighing laboratory, and laboratory technician error. These uncertainties were minimized by making use of repeat measurements and central environmental control as described in *Section 0*. The initial and final filter masses ($M_{i\ or\ f}$) were calculated by using *Equation 2.1*:

$$M_{i\ or\ f} = \frac{(M_1 + M_2 + M_3 + \cdots)}{N}$$

Equation 2.1. Initial- and final filter mass concentration in grams (g).

where M_1, M_2, and M_3 are the recorded filter masses in grams (g) divided by N, the number of repeated measurements for each filter.

Instrument flow rate measured by Gilibrator II flow calibrator

The instrument flow calibration process, used in both Method I and II *(see Section 2.3.2.1.2 and 0)*, was also subject to precision uncertainties. Similarly to the filter masses, repeat measurements were used to minimise the uncertainties. The initial and final flows ($F_{i\ or\ f}$) were calculated by using *Equation 2.2*, below:

$$F_{i\ or\ f} = \frac{(F_1 + F_2 + F_3 + \cdots + F_{10})}{N}$$

Equation 2.2. Initial- and final instrument flow in litres per minute ($L.min^{-1}$).

where F_1, F_2, $F_{...}$, and M_{10} are the recorded flow rates in litres per minute ($L.min^{-1}$) divided by N, the number of repeated measurements for each instrument. The flow calibration was accepted if the initial and final flows ($F_{i\ or\ f}$) were within five per cent (±5%) of the required flow.

2.3.3.1.2. Instrument resolution

The instrument uncertainties are determined by the manufacturer specifications. The photometric instruments have a resolution sensitivity (*RS*) of ±0.1% of the reading, however, if the calculated value was below 1 $\mu g.m^{-3}$, an uncertainty ±1 $\mu g.m^{-3}$ was assigned. The relative uncertainty (RU_{CPM4}) in $\mu g.m^{-3}$, for individual continuous mass concentration measurements (C_{PM4}) in $\mu g.m^{-3,}$ were calculated using *Equation 2.3*, below:

$$RU_{C_{PM4}} = \frac{RS \times C_{PM4}}{100}$$

Equation 2.3. Relative uncertainty for individual photometric measurements ($\mu g.m^{-3}$).

2.3.3.2. Systematic errors

The systematic errors identified during this study are related to instrument calibrations, zero offsets, environmental factors, and unaccounted for factors. The errors and associated corrections are discussed below.

2.3.3.2.1. Instrument calibrations

Photometric monitoring instruments

The photometric instruments used for the continuous monitoring (Method I) are operated using the existing calibration factor of one (1), which is based on the annual factory calibration done by the manufacturer *(see*

Section 2.3.2.1.1). The mass concentration recorded by the instrument can be influenced by various factors such as the micro-environment in which sampling occurs as well as the physical and chemical composition of the particles being sampled. It is thus acknowledged that the instruments are susceptible to the over- or underestimation of particulate mass concentrations. These uncertainties were identified through the use of collocated *Evaluation Study I* (Method III) as described in *Sections 0.* The absolute- (AE_{CPM4}) and relative error (RE_{CPM4}) in the mass concentrations calculated by the photometric instruments were investigated by using *Equation 2.4* and *Equation 2.5*, respectively:

$$AE_{C_{PM4}} = [C_{PM4} - G_{PM4}]$$

Equation 2.4. Absolute error in mass concentration from photometric instruments (µg.m^{-3}).

$$RE_{C_{PM4}} = \frac{[C_{PM4} - G_{PM4}]}{G_{PM4}} \times 100$$

Equation 2.5. The relative error in mass concentration from photometric instruments (%).

where C_{PM4} is the time-integrated continuous PM_4 mass concentration µg.m^{-3} and G_{PM4} is the gravimetric mass concentration in µg.m^{-3}. In addition to the above mentioned specific photometric calibration factors calculated *(see Section 2.4.2.1.3)* for the various sampling environment. These calibration factors were applied to the data *(see Section 2.4.3.1.1)*.

Microbalance

The XP26 DeltaRange Microbalance used in the study (Method II) was subject to annual manufacturer calibrations, however, calibration weights (1g and 20g) were used prior to each weighing session *(see Section 0)* to identify any instrument drift. The relative error (RE_M), in percentage (%), associated with the calibration of the electronic scale, for each weighing session, was calculated using *Equation 2.6*:

$$RE_{Mx} = \frac{[(M_1 + M_2 + M_3) - M_x]}{M_x} \times 100$$

Equation 2.6. The relative error in the calibration of the XP26 DeltaRange Microbalance (%).

where M_1, M_2, and M_3 are the recorded masses in grams (g) for the weight and Mx is the actual mass of the specific weight (either 1g or 20g) in grams (g). The filter masses recorded during the specific session were corrected based on the relative error observed.

2.3.3.2.2. Zero offsets

In addition to the main calibration uncertainties, as described above, the instruments could be subject to zero drifts which may require an offset to be applied to the data. The occurrence of zero drift is significantly reduced by using the zeroing function for each individual instrument (most instruments have this function).

During this study, the zero calibration function for all instruments (photometric, microbalance, flow calibrators) were actively used as suggested by the manufactures. It is thus assumed that no further offsets, regarding zero drift, need to be applied to the data.

2.3.3.2.3. Environmental and other unaccounted for factors

The study was conducted over several years and across various regions which differ significantly with regard to climate, weather, land use, socio-economics and emission sources as described in the study area characterisation *(see Section 2.2)*. It is also important to note that the drivers of both ambient and indoor sources of particulate pollution are highly dependent on the above-mentioned factors. The time during which each household was sampled might introduce inter-household, -settlement, and -region biases. On the other hand, there might also be biases across the settlements and regions. For example, a single extreme weather event occurring in a specific season could influence the behaviour of the residents within the specific house being sampled, which might not be consistent with houses being sampled at a later stage during the monitoring campaign. A second example is linked to the availability of disposable income that a household might have during the course of the sampling campaign. Residents might be inclined to use more solid fuels during winter for heating if they had the available funds to procure the fuel of choice, leading to increased emissions.

There are a number of factors that could influence the measurements made within the residential indoor environment, such as i) ventilation, ii) air exchange rates, iii) gaseous pollutant concentrations, iv) physical particle properties; v) energy efficiency of the residence; vi) behavioural characteristics of residents; and vii) the presence of specific sources. Some inferences, related to the above mention, can be made based on the household questionnaire survey data described in *Section 2.3.2.5.3*.

All the factors mentioned above lead to variability, and the only way to account for all these sources of error is to have long-term sampling campaigns over various regions. This particular research design did not have the necessary infrastructure and capacity to investigate all of these aspects in-depth, and thus it was considered outside the scope of this study.

The author acknowledges that there are errors resulting from clear causes. These errors have been evaluated and corrected where possible. The assumptions made regarding various uncertainties have been clearly stated where applicable. However, there might still be errors present, resulting from unknown causes, which have been overlooked. The final data preparation and quality control procedures are discussed in the following section.

2.4. Data preparation and quality control

There are three (3) levels of data sets used, namely, i) 'Level_00 – Raw Data', ii) 'Level_01 – Raw Data Combined', and iii) 'Level_02 – Quality Controlled Data'.

The first mentioned refers to the data obtained through the data collection process described in *Section 2.3.1.1* above. This data is kept secure and is mainly used for quality control. Only selected persons have access so as to prevent sensitive identifiable information from being used without permission. The 'Level_01' data sets were produced by digitising and integrating raw data files from different methods. The previously mentioned was then subject to anonymising and quality control leading to the 'Level_02' data sets which were used for further statistical analysis.

Data collected for this study were subdivided into thirteen (13) individual 'Level_02' data sets. All *.xlsx* files were imported into STATISTICA Version 13 *(TIBCO Software Inc., 2017)* software, where it was converted to a *.sta* files that were used for further statistical analysis as described in *Section 2.4.4*. The specific preparations for each data set and associated variables are discussed in further detail below.

2.4.1. Study area characterisation

2.4.1.1. Primary fuel use in South Africa

The fuel use data *(see Section 2.3.2.5.1)* extracted from the 2011 national census were compiled into a single *.xlsx* files according to *Table 2.13*. The fuel types (1-6) included electricity, gas, paraffin, wood, coal, and dung. The purpose for which it was used were identified as cooking or heating. The data was categorised by the nine provinces (1-9) of South Africa.

Table 2.13 The primary fuel use variables obtained from the 2011 national census data.

No.	Variable	Type	Units	Range/*Classes*
1	Fuel Type	Text	-	*1-6*
2	Use	Text	-	*1-2*
3	Province	Text	-	*1-9*
4	No. of Households	Number	%	0-100

2.4.1.2. Demographics and socio-economics of selected settlements

The socio-economic data *(see Section 2.3.2.5.1)* obtained from the 2011 national census were compiled into a single *.xlsx* file. The variables included are listed in *Table 2.14*. The annual household income (AHI) is represented by thirteen (13) classes. The first class represents R0 income followed by R4 800 (Class 2). The subsequent classes are calculated by multiplying the previous with two, thus class three equals class two multiplied by two. The population age is divided into eighteen (18) classes starting at ≤ 4 of age. The following classes are calculated by adding 5 years to the previously defined class. The last class represents the population ≥ 85 of age. The housing type is divided into thirteen (13) classifications included, for example, brick, traditional, and informal. Both the cooking and heating fuel types are divided into ten (10) categories. In addition to those mention in *Section 2.4.1.1*, it also includes solar, other, and unspecified classes.

Table 2.14 The demographic and socio-economic variables extracted from 2011 national census data.

No.	Variable	Type	Units	Range/*Classes*
1	Settlement	Text	-	*1-5*
2	Local Municipality	Text	-	*1-5*
3	District Municipality	Text	-	*1-5*
4	Province	Text	-	*1-3*
5	AHI by Income Classes	Number	% of Households	*1-13*
6	Population by Age Groups	Number	% of People	*1-18*
7	Housing by Types	Number	% of Households	*1-13*
8	Cooking by Fuel Type	Number	% of Households	*1-10*
9	Heating by Fuel Type	Number	% of Households	*1-10*

2.4.1.3. Climate of the study area

The data were extracted, tabulated, and compiled into a single *.xlsx* file according to *Table 2.15*. The temperature is represented by seven (7) categories, including the average daily temperature (minimum, mean, and maximum), maximum temperature (highest maximum and highest mean), and the minimum temperature (lowest minimum and lowest mean). The number of days with a specific amount of rainfall is given in five (5) classes including precipitation >=0.1 mm, >=1 mm, >=5 mm, >=10 mm, and >=30 mm. The relative humidity is presented by five (5) classes including the mean RH at 08h00, 14h00. 20h00, as well as the minimum and maximum.

Table 2.15 The climate variables extracted from SAWS climate data.

No.	Variable	Type	Units	Range/*Classes*
1	Site	Tex	-	*1-4*
2	Year Range	Number	yyyy	1989-2010
3	No. of Years	Number	yy	18-29
4	Month	Text	-	*1-12*
5	Temperature	Number	°C	*1-7*
6	Rainfall	Number	Days	*1-5*
7	Relative Humidity	Number	%	*1-5*

2.4.2. Evaluating photometric instruments (Objective I)

Objective I had three specific sub-objectives *(see Section 1.4)* each of which required its own specific data set. The included variables are given in *Table 2.16*.

Variables one (1) to twelve (12) are considered common and applicable to all the following data sets. The classifications include season (spring, summer, winter), settlement (KwaDela, KwaZamokuhle, Jouberton, Agincourt, Giyani), environment type (urban, rural, or laboratory), dwelling type (formal, formal RDP, informal), household fuel use (ISFB, NSFB, OSFB), and the specific micro-environment (kitchen, living room, bedroom). The calculation and handling of data for specific variables in each data set are discussed in further detail below.

Table 2.16 The arrangement of variables used for Evaluation Study I, II, and III.

Data Set	No.	Variable	Type	Units	Range/*Classes*
Common variables	1	Date	Number	yyyy/mm/dd	-
	2	Year	Number	yyyy	2013-2017
	3	Month	Number	mm	1-12
	4	Day	Number	dd	0-31
	5	Time	Number	hh:mm	-
	6	Season	Text	-	*1-3*
	7	Settlement	Text	-	*1-5*
	8	Household ID	Number	1-251	*Hxxx*
	9	Environment Type	Text	-	*1-3*
	10	Dwelling Type	Text	-	*1-3*
	11	Household Fuel Use	Text	-	*1-3*
	12	Micro-environment	Text	-	*1-3*
Photometric calibration factors	13	Instrument	Text	-	*1-3*
	14	Continuous PM_4	Number	$\mu g.m^{-3}$	-
	15	Gravimetric PM_4	Number	$\mu g.m^{-3}$	-
	16	Photometric Calibration Factors	Number	-	-

Table 2.16 (Continued)

Instrument inter-comparison	13	SidePak PM_4	Number	$\mu g.m^{-3}$	-
	14	DustTrak PM_4	Number	$\mu g.m^{-3}$	-
	15	DustTrak II PM_4	Number	$\mu g.m^{-3}$	-
Size fraction inter-comparison	13	Continuous PM_1	Number	$\mu g.m^{-3}$	-
	14	Continuous $PM_{2.5}$	Number	$\mu g.m^{-3}$	-
	15	Continuous PM_4	Number	$\mu g.m^{-3}$	-
	16	Continuous PM_{10}	Number	$\mu g.m^{-3}$	-

2.4.2.1. Photometric calibration factors

The photometric calibration factor data set was composed from Method III, as described in *Section 0*, as well as results from literature. In addition to the common variables described above, a distinction is also made between the instruments used to collect the data, namely SP, DT, and DT II. Variables fourteen (14) to sixteen (16) were calculated as described below. Note that the data were averaged to a 24-hour period.

2.4.2.1.1. Continuous mass concentration determination

The mass concentrations were given by the instruments in milligram per cubic meter ($mg.m^{-3}$). These measurements were converted to microgram per cubic meter ($\mu g.m^{-3}$) by using *Equation 2.7* below:

$$PM4_{(\mu g.m^{-3})} = PM4_{(mg.m^{-3})} \times 10^3$$

Equation 2.7. PM_4 mass conversion from $mg.m^{-3}$ to $\mu g.m^{-3}$.

Measurements that were either below the lower limit of detection and above the upper limit of detection were removed *(see Section 2.3.2.1.1)* from the data. The measurements were then averaged according to the field logs so as to be comparable to the gravimetric mass concentrations obtained from the intermittent filter sampling for the same period.

2.4.2.1.2. Gravimetric mass concentration determination

The gravimetric mass refers to the collected particulate mass after exposure of the collection substrate. The gravimetric PM_4 mass concentration, in $\mu g.m^{-3}$, was calculated from the laboratory logged mass data and the sampled volume using *Equation 2.8*:

$$PM4_{(\mu g.m^{-3})} = \frac{\left((M_f - M_i) - (B_f - B_i)\right)}{V_T} \times 10^6$$

Equation 2.8. Gravimetric mass concentration in microgram per cubic meter ($\mu g.m^{-3}$).

, where PM_4 is the gravimetric PM_4 concentration in $\mu g.m^{-3}$, M_f is the post-exposure filter weight in g, M_i is the pre-exposure filter weight in g, B_f is the mean post-exposure blank filter weight in g, B_i is the mean pre-exposure blank filter weight in g, and V_T is the total volume of air sampled in m^3. The results were then converted from g to µg by multiplying with 10^6 *(NIOSH, 1998; World Health Organization, 1976).*

2.4.2.1.3. Ratio of over- and underestimation

The ratios for the over-and underestimation (PCG_{Ratio}) of the continuous PM_4 by the photometric instruments were calculated by using *Equation 2.9*.

$$PCG_{Ratio} = \frac{C_{PM4}}{G_{PM4}}$$

Equation 2.9. Ratio of photometric instrument over-and underestimation.

, where C_{PM4} is the time-integrated continuous PM_4 mass concentration in $\mu g.m^{-3}$, divided by the gravimetric PM_4 mass concentration (G_{PM4}) in $\mu g.m^{-3}$. The photometric instruments overestimate the mass concentration at PCG_{Ratio} above one (>1) and underestimate at ratios below one (<1).

2.4.2.1.4. Photometric calibration factor determination

The photometric calibration factors (PCF) were calculated by using *Equation 2.10*. Comparing PM_4 mass concentrations obtained from the continuous photometric monitoring instruments and the reference intermittent gravimetric sampling method provides a specific calibration factor for each instrument and varying indoor microenvironments.

$$PCF = \frac{G_{PM4}}{C_{PM4}}(CCF)$$

Equation 2.10. Photometric calibration factor *(TSI Incorporated, 2014)*.

, where G_{PM4} is the gravimetric mass concentration in $\mu g.m^{-3}$, divided by the time-integrated continuous PM_4 mass concentration (C_{PM4}) in $\mu g.m^{-3}$, multiplied by the current calibration factor (*CCF*).

2.4.2.2. Inter-comparison of different photometric instruments

The individual *.txt* data obtained from the collocated instrument comparison *(see Section 0)* were combined into a single *.xlsx* file according to *Table 2.16*. The data were subject to the same calculations and quality control described in *Section 2.4.2.1*, however, the data was averaged on a five-minute basis.

2.4.2.3. Inter-comparison of different size fractions sampled with photometric instruments

The individual *.txt* data obtained from the collocated instrument comparison *(see Section 0)* were combined into a single *.xlsx* file according to *Table 2.16*. The data were handled as described above in *Section 2.4.2.1.1*. The 5-minute averaged raw data was used in this collocated comparison. The extreme values (mass concentrations above 10 000µg.m^{-3}) were not removed from the data for this comparison. The main reason being that the difference in the measured values of the various instruments was investigated, this includes the variations in the extreme values.

2.4.3. Characterising respirable PM concentrations (Objective II & III)

The characterisation of particulate matter was divided into two separate objectives, namely, objective II and III *(see Section 1.4)*. It required the use of multiple data set as given in *Table 2.17* below. Objective II included both the continuous and gravimetric data sets, whereas objective III only made use of the gravimetric data set. The calculations and handling of data for specific variables in each data set are discussed in further detail below.

Table 2.17 The arrangement of variables used for Objective II and III.

Data Set	No.	Variable	Type	Units	Range/*Classes*
Common Variables	1-12*				
Continuous	13	Continuous PM_4	Number	µg.m^{-3}	
	15	Converted $PM_{2.5}$	Number	µg.m^{-3}	
Gravimetric	13	Gravimetric PM_4	Number	µg.m^{-3}	
	14	Elements	Number	µg.m^{-3}	
	15	Enrichment Factor	Number		

* **Common variables listed in *Table 2.16*.**

2.4.3.1. Continuous indoor PM_4

The continuous PM_4 namely variable thirteen (13) was computed based on *Equation 2.7 (see Section 2.4.2.1.1)*. The data were presented as five-minute averaged measurements. These measurements represent the readings as recorded with the initial factory calibration factor of one (1). However, the purpose of Objective I was to provide specific calibration factor for the particular environments sampled during this study. The application of these PCFs is given below.

2.4.3.1.1. Continuous mass concentration correction by PCF

Variable fourteen (14), the corrected continuous PM_4 mass concentration (CC_{PM4}) in µg.m^{-3} is calculated based on *Equation 2.11*:

$$CC_{PM4} = C_{PM4} \times PCF$$

Equation 2.11. Correction of PM_4 by PCF.

where C_{PM4} is the uncorrected continuous PM_4 mass concentration in $\mu g.m^{-3}$ multiplied by the selected PCF *(see Chapter 3, Section 3.1, Table 3.1)*.

The data was scrutinised for outlier values above 10 000 $\mu g.m^{-3}$, which could potentially skew the data upon further analysis. Fifty-two (52) cases of concern were identified and summarised in *Table 2.18*. These cases mostly occurred within the indoor solid fuel burning (ISFB) households in KwaDela and KwaZamokuhle at or around the expected morning and evening peak burning periods. Three cases were identified for outside solid fuel burning (OSFB) households situated in Agincourt and Giyani. This case occurred on a winters evening during the period when the household is expected to be cooking in close proximity to the house and thus impact on the indoor particulate levels. The cases occurring in the non-solid fuel-burning (NSFB) houses were mostly single value outliers, which could possibly have resulted from activities that are specific or unique to the given house or be attributed to instrument artefacts. A total of a two-hundred-and-thirty-eight (238) individual five-minute averaged data points were excluded from the data set.

Table 2.18 Extreme outlier cases excluded from the final data analysis.

Settlement	House No.	Type of House	Case	Date	Time	No. of 5-min averaged values removed
KwaDela	H001	ISFB	1	2013/07/05	07:55 to 08:15	3
	H002	ISFB	2	2014/02/27	22:35 to 22:50	4
			3	2014/09/10	19:25	1
			4	2014/09/15	21:40	1
	H003	NSFB	5	2015/02/12	18:30	1
	H004	ISFB	6	2014/07/24	18:15	1
	H005	ISFB	7	2013/08/30	18:15	1
	H008	ISFB	8	2013/08/19	17:45 to 17:55	3
			9	2013/08/20	06:15 to 06:35	3
			10	2014/08/10	10:00	1
	H009	ISFB	11	2014/08/20	12:55	1
	H011	ISFB	12	2014/03/13	12:00 to 12:10	3
	H014	ISFB	13	2013/07/05	16:45 to 16:50	2
			14	2013/07/17	04:10	1
			15	2014/08/21	10:25 to 10:45	5
			16	2014/08/29	7:20	1
			17	2014/08/30	09:25 to 09:30	2

Table 2.18 (Continued)

Settlement	House No.	Type of House	Case	Date	Time	No. of 5-min averaged values removed
KwaDela (Cont.)	H015	NSFB	18	2014/05/05	19:15	1
			19	2015/03/16	14:40	1
			20	2015/03/17	10:10	1
	H016	ISFB	21	2013/08/15	05:05 to 05:15	3
			22	2015/03/17	16:35 to 18:45	2
	H021	ISFB	23	2015/03/17	06:20 to 07:20	3
	H022	NSFB	24	2014/08/23	16:50	1
	H023	ISFB	25	2015/03/04	06:40 to 07:30	4
			26	2015/03/04	20:40	1
			27	2015/03/07	21:50 to 21:55	2
			28	2015/03/10	07:20	1
KwaZamokuhle	H025	ISFB	29	2016/08/12	17:10	1
			30	2016/08/18	16:30	1
	H026	ISFB	31	2016/08/06	08:00 to 18:20	8
			32	2016/08/09	07:25 to 07:35	3
	H029	ISFB	33	2016/03/01	22:05 to 22:10	2
	H031	ISFB	34	2015/10/04	01:25 to 03:25	29
			35	2015/10/15	07:30 to 08:10	3
			36	2015/10/16	14:25 to 17:50	3
			37	2015/10/17	09:05	1
			38	2015/10/18	08:45 to 08:50	2
			39	2016/03/10	12:15	1
			40	2016/08/11	04:45 to 05:45	13
			41	2016/08/12	04:45 to 06:30	22
			42	2016/08/13	07:00 to 22:55	25
			43	2016/08/20	07:45 to 07:50	2
			44	2016/08/24	05:00 to 05:50	11
			45	2016/08/27	08:45 to 16:45	3
			46	2016/09/03	07:25	1
	H032	ISFB	47	2015/10/31	08:05 to 08:15	3
Jouberton	H151	NSFB	48	2016/04/19	22:05 to 23:05	13
Agincourt	H082	OSFB	49	2016/05/19	17:45 to 19:55	27
Giyani	H034	OSFB	50	2017/02/08	17:45	1
	H038	OSFB	51	2017/07/19	16:25 to 16:50	6
			52	2017/07/23	20:15 to 20:25	3
					Total	**238**

2.4.3.2. Gravimetric and elemental indoor PM_4

The gravimetric PM_4, namely variable thirteen (13), was calculated using *Equation 2.8 (see Section 2.4.2.1.2)* and presented as 24-hour averaged measurements. The calculations associated with variables fourteen (14) and fifteen (15), namely the elemental mass concentrations and enrichment factors, are given below.

2.4.3.2.1. Blank elemental mass concentration determination

The blank Mixed Cellulose Ester (MCE) filters were subject to the same handing and analysis procedures as the exposed MCE filters *(see Section 0)*. The mean values of Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Pd, Ag, Cd, In, Sn, Sb, I, Ba, Ce, W, Pt, Au, Hg, Tl, Pb, and Bi in the blank MCE filters were 0.02, 0.01, <0.01, 0.03, <0.01, 0.02, 0.22, 0.04, 0.14, 0.02, 0.02, 0.05, 0.02, 0.09, 0.03, 0.07, 0.41, 0.52, 0.18, 0.05, <0.01, <0.01, 0.01, 0.01, 0.21, 0.01, <0.01, 0.33, <0.01, 8.22, <0.01, 1.17, 0.06, 0.32, 0.12, 0.29, 0.08, 1.40, 0.12, 0.16, 0.11, 0.15, 0.13, 0.18, and 0.19 µg.cm^{-2}, respectively.

The majority of the blank values were lower than the limit of detections (LOD) values *(see Table 2.7)*, however, Na, Cu, Zn, Pd, Cd, In, Sn, Sb, I, and Ce above the LOD. This indicated that the filter composition itself might impede the observed concentrations of these elements within the exposed filters. All the results reported in *Chapter 4, Sections 4.1.2.1* and *4.1.2* were subject to blank filter correction as described below.

2.4.3.2.2. LOD and LOQ of the elemental mass concentrations

The limit of detection (LOD) and limit of quantification (LOQ) for the WD-XRF analysis is defined by *Equation 2.12* and *Equation 2.13* below:

$$LOD\ (\mu g.cm^{-2}) = \frac{SD_B \times 3.3}{S_{Cal}}$$

Equation 2.12. WD-XRF detection limits (µg.cm^{-2}).

$$LOQ\ (\mu g.cm^{-2}) = \frac{SD_B \times 10}{S_{Cal}}$$

Equation 2.13. WD-XRF quantification limits (µg.cm^{-2}).

, where SD_B is the standard deviation of the average element concentration of the blank filters in µg.cm^{-2} and S_{Cal} is the slope of the calibration regression line *(Shrivastava & Gupta, 2011)*. The LOD and LOQ values were presented in *Table 2.7* above. The following elements were above the LOD for i) >=75%: Na, Mg, Al, Si, S, K, Ca, Zn, and Sn; ii) >=50-74%: P, and Cl; ii) >=25-49%: Ti, Fe, Cu, Sr, Pd, Cd, In,

Sb, I, Ce, W, Pt, Au, Hg, Tl, Pb, Bi; and iv) <25%: V, Cr, Mn, Co, Ni, Ga, Ge, As, Se, Br, Rb, Y, Y, Zr, Nb, Mo, Ag, and Ba of the exposed samples.

2.4.3.2.3. Elemental mass concentration determination

The elemental mass (*EM*) concentrations, obtained from the WD-XRF analysis *(see Section 0)*, were given in µg.cm^{-2} after which it was converted to µg.m^{-3} using *Equation 2.14*:

$$EM_{(\mu g.m^{-3})} = \frac{(EM_S - EM_B)A}{V_T}$$

Equation 2.14. Conversion of element mass concentration from µg.cm^{-2} to µg.m-^{3}.

where EM_S is the element mass concentration of the sample in µg.cm^{-2}, EM_B is the average element concentration of the blank filters in µg.cm^{-2}, A is the exposed area of the 37mm filter in cm^{-2}, and V_T is the total volume of air sampled in m^3.

The exposed area of the filter was calculated to be 8.40 cm^{-2} by using *Equation 2.15*:

$$A_{(\mu g.cm^{-2})} = \pi r^2$$

Equation 2.15. The exposed area of 37mm filter (µg.cm^{-2}).

where r is the radius of the exposed part of the filter in centimetre (cm). In addition to the above, both the detected and undetected element mass concentrations were also calculated. The total detected elemental mass *($EM_{(D)}$) was calculated using* *Equation 2.16*:

$$EM_{(D)} = (EM_n + EM_n + EM_n \ldots)$$

Equation 2.16. The detected element mass concentration (µg.cm^{-2}).

where $EM_{(D)}$ is the sum of the mass concentrations of the all detected elements *(EM_n)*.in µg.m^{-3}. The undetected elemental mass concentration *($EM_{(u)}$)* was calculated using *Equation 2.17*:

$$EM_{(U)} = PM4 - EM_{(D)}$$

Equation 2.17. The undetected element mass concentration (µg.cm^{-2}).

where $EM_{(u)}$ is the difference between the gravimetric mass and the total detected elemental concentration in µg.m^{-3}.

2.4.3.2.4. Enrichment factor determination

Enrichment factors (EF) for individual elements in the PM_4 fraction relative to Mason's *(1966)* average crustal rock composition were calculated using Al as the reference element according to *Equation 2.18*:

$$Enrichment\ Factor\ (EF) = \frac{[C(X)/C(Al)]_{PM4\ aerosol}}{[C(X)/C(Al)]_{crust}}$$

Equation 2.18. Enrichment factor using crustal Al as a reference element.

where *C(X)* is the concentration of a selected element and *C(Al)* the concentration of aluminum in the aerosol sample or the reference crustal rock. The crustal elements, as given by Mason, are summarised in *Table 2.19*. The EFs were calculated for each individual receptor site cased on community type, settlement, season, and household fuel use classification.

Table 2.19 Masons' crustal elements arranged from most- to least abundant in weight percentage and parts per million where specified.

Z	Element	Symbol	% or (ppm)	Z	Element	Symbol	% or (ppm)	Z	Element	Symbol	% or (ppm)	Z	Element	Symbol	% or (ppm)
8	Oxygen	O	46.600	37	Rubidium	Ru	0.012	66	Dysprosium	Dy	(5.000)	71	Lutetium	Lu	(0.800)
14	*Silicon	Si	27.720	23	*Vanadium	V	0.011	72	Hafnium	Hf	(5.000)	80	*Mercury	Hg	(0.500)
13	*Aluminium	Al	8.130	28	*Nickel	Ni	0.008	5	Boron	B	(3.000)	53	*Iodine	I	(0.300)
26	*Iron	Fe	5.000	30	*Zinc	Zn	0.007	35	*Bromine	Br	(3.000)	48	*Cadmium	Cd	(0.200)
20	*Calcium	Ca	3.630	7	Nitrogen	N	0.005	50	*Tin	Sn	(3.000)	51	*Antimony	Sb	(0.200)
11	*Sodium	Na	2.830	58	*Cerium	Ce	(46.000)	68	Erbium	Er	(3.000)	69	Thulium	Tm	(0.200)
19	*Potassium	K	2.590	29	*Copper	Cu	(45.000)	70	Ytterbium	Yb	(3.000)	83	*Bismuth	Bi	(0.200)
12	*Magnesium	Mg	2.090	39	*Yttrium	Y	(40.000)	4	*Beryllium	Be	(2.000)	47	*Silver	Ag	(0.100)
22	*Titanium	Ti	0.440	3	*Lithium	Li	(30.000)	32	*Germanium	Ge	(2.000)	49	*Indium	In	(0.100)
1	Hydrogen	H	0.140	41	*Niobium	Nb	(24.000)	33	*Arsenic	As	(2.000)	18	Argon	Ar	(0.040)
15	*Phosphorus	P	0.118	60	Neodymium	Nd	(24.000)	73	Tantalum	Ta	(2.000)	46	*Palladium	Pd	(0.010)
25	*Manganese	Mn	0.100	27	*Cobalt	Co	(23.000)	92	Uranium	U	(2.000)	78	*Platinum	Pt	(0.005)
9	Fluorine	F	0.070	57	Lanthanum	La	(18.000)	42	*Molybdenum	Mo	(1.000)	79	Gold	Au	(0.005)
16	*Sulphur	S	0.052	31	*Gallium	Ga	(15.000)	55	Cesium	Cs	(1.000)	2	Helium	He	(0.003)
38	*Strontium	Sr	0.045	82	*Lead	Pb	(15.000)	63	Europium	Eu	(1.000)	52	Tellurium	Te	(0.002)
56	*Barium	Ba	0.040	90	Thorium	Th	(10.000)	67	Holmium	Ho	(1.000)	44	Ruthenium	Ru	(0.001)
6	Carbon	C	0.032	62	Samarium	Sm	(7.000)	74	*Tungsten	W	(1.000)	45	Rhodium	Rh	(0.001)
17	*Chlorine	Cl	0.020	59	Praseodymium	Pr	(6.000)	81	*Thallium	Tl	(1.000)	75	Rhenium	Re	(0.001)
24	*Chromium	Cr	0.020	64	Gadolinium	Gd	(6.000)	34	*Selenium	Se	(0.900)	76	Osmium	Os	(0.001)
40	*Zirconium	Zr	0.016	21	Scandium	Sc	(5.000)	65	Terbium	Tb	(0.900)	77	Iridium	Ir	(0.001)

* **Element included in analysis**

2.4.3.3. Household Surveys

The household survey data *(see Section 2.3.2.5.3)* extracted from the questionnaire interviews conducted in each settlement were compiled into a single .xlsx file according to *Table 2.20*. This included the monthly income, household population size, the housing types, as well as the primary fuels used for cooking and heating activities. The class divisions were the same as described for the national census data. Note that the data was only extracted for the 251 households sampled in the study. The ethical clearance process associated with the data collection is described in *Section 2.6*.

Table 2.20 The demographic and socio-economic variables extracted from household questionnaire surveys.

No.	Variable	Type	Units	Range/*Classes*
1	Settlement	Text	-	*1-5*
2	Monthly Income	Number	% of Households	*1-8*
3	Household Size	Number	% of Households	*1-11*
4	Housing by Types	Number	% of Households	*1-2*
5	Cooking by Fuel Type	Number	% of Households	*1-5*
6	Heating by Fuel Type	Number	% of Households	*1-6*

2.4.4. Meteorology of the study area

2.4.4.1. Synoptic circulation

The daily synoptic charts *(see Section 2.3.2.5.2)* for each sampling campaign *(see Table 2.2)* were qualitatively analysed and tabulated into an *.xlsx* file according to *Table 2.21*. The synoptic conditions are classified into ten (10) classes according to the circulation types associated with i) fine-weather (continental anticyclones and coastal lows), ii) tropical disturbances (easterly waves and easterly lows), and iii) temperate mid-latitude disturbances (westerly wave, cut-off lows, southerly meridional flow, ridging anticyclone, west-coast trough, and cold snap). This classification is done based on the prevailing surface conditions as described in *Tyson & Preston-Whyte (2004:184)*.

Table 2.21 The arrangement of synoptic circulation variables extracted from the SAWS data.

No.	Variable	Type	Units	Range/*Classes*
1	Settlement	Text	-	*1-5*
2	Date	Number	yyyy/mm/dd	
3	Season	Text	-	*1-3*
4	Fine-weather	Number	0 or 1	*1-2*
5	Tropical disturbances	Number	0 or 1	*1-2*
6	Temperate mid-latitude disturbances	Number	0 or 1	*1-6*
7	No Data Available	Number	0 or 1	-

2.4.4.2. Meteorology

The relevant data were extracted and arranged into a single hourly averaged *.xlsx* data set according to *Table 2.22*.

Table 2.22 The meteorological variables for SAWS and C.R.G. data.

No.	Variable	Type	Units	Range/*Classes*
1	Date & Time	Number	yyyy/mm/dd hh:mm	-
2	Date	Number	yyyy/mm/dd	-
3	Year	Number	yyyy	2013-2017
4	Month	Number	mm	1-12
5	Day	Number	dd	0-31
6	Time	Number	hh:mm	-
7	Hour	Number	hh	0-23
8	Settlement	Text	-	*1-5*
9	Season	Text	-	*1-4*
10	Temperature	Number	°C	-
11	Humidity	Number	%	-
12	Pressure	Number	hPa	-
13	Wind Direction	Number	°	0-360
14	Wind Speed	Number	$m.s^{-1}$	-

2.4.4.3. Wind Roses

The hourly wind speed and wind direction observational data *(see Section 2.3.2.5.2)* were extracted and arranged according to the requirements for input into the WRPLOT View™ Version 8.0.2 *(Lakes Environmental Software, 2018)* software. The data were compiled into *.xlsx* files for each sampling campaign *(see Table 2.2)* which were then imported into the software for further analysis. The variables and ranges are giving in *Table 2.23*.

Table 2.23 The arrangement of wind rose variables for input into WRPLOT View™ software *(adapted from Thé et al., 2016).*

No.	Variable	Type	Units	Range/*Classes*
1	Year	Number	yyyy	2013-2017
2	Month	Number	mm	1-12
3	Day	Number	dd	1-31
4	Hour	Number	hh	0-23
5	Wind Direction	Number	Deg	0-360
6	Wind Speed	Number	m/s	-

2.5. Statistical data analysis techniques

The statistical analysis performed to reach the specific objectives are discussed below. All analyses were conducted using STATISTICA Version 13 *(TIBCO Software Inc., 2017)* and WRPLOT View™ Version 8.0.2 *(Lakes Environmental Software, 2018)*. The final results were visually presented for better understand and interpretation using the following statistical techniques:

2.5.1. Descriptive statistics

Descriptive statistics were used to describe the basic characteristics such as the central tendency and distribution of the data sets. The data is often categorised by settlement, season, year, month, household ID, type of environment, type of dwelling, household fuel use, micro-environment, date, and hour of the day.

2.5.1.1. Central tendency

2.5.1.1.1. Descriptive tables

The central tendency of the data were characterised by making use of descriptive tables containing some of the following elements, namely the minimum (min), maximum (max), mean, median, standard deviation (SD), standard error (SE), 95% confidence intervals, low- (LQ) and upper quartiles (UQ), interquartile range (IQR), the 1st and 99th percentile. In *Chapter 5 Section 0*, it was used to present the observed surface meteorological conditions (*see Section 2.4.4.2*). In *Chapter 3 Section 3.1.1.1, 3.2.2, 3.3.2,* and *3.3.3.1* it was used to present the particulate mass concentrations (*see Sections 2.4.2.1, 2.4.2.2,* and *2.4.2.3*).

2.5.1.1.2. Box plots

Box plots are often used to illustrate the tendencies, where the mid-point is the median, the top and bottom of the box represents the 75th and 25th percentiles, and the top and bottom end of the whiskers indicate the 99th- and 1st percentiles. Categorised box plots were used in *Chapter 5 Section 5.1.3* to present the diurnal variability of the temperature and relative humidity (*see Section 2.4.4.2*) for each settlement, classified by season.

2.5.1.1.3. Variability plots

Variability plots were used to organise and represent data based on the nested hierarchy. This was specifically useful to evaluate the variability of a single factor that appears within and might be impacted by several organising factors. This analysis also provides grouped medians based on the nested hierarchy used. These graphs may be presented as either raw data or box plots.

The variability box plots are slightly different from the previously described as the mid-point is the median, the top and bottom of the box represents the 75th and 25th percentiles, and the top and bottom end of the whiskers indicate the non-outlier range (this is defined by the statistical program). The box plot version was specifically used in *Chapter 5 Section 0* to investigate the variability of surface temperature, relative humidity, and wind speed based on the hierarchy of season, settlement, and year. In *Chapter 3 Section 3.1.2* it was used to show the variability in the PCFs.

2.5.1.2. Distribution

The distribution of the data is shown through the use of frequency tables, cumulative frequency distribution curves, stacked column plots, line plots, and wind roses.

2.5.1.2.1. Stacked column plots

The stacked percentage column plots were used to present the distribution of various categories forming part of a single variable. These plots were specifically used in *Chapter 2 Section 2.2* to present the percentage of occurrence for the primary fuels used for cooking and heating activities in South Africa (*see Section 2.4.1.1*) categorised by province. It was also used to display the frequency percentages related to the population by age group, annual household income, housing type, household size, and household fuel use categorised by settlements for both the national census and household surveys. In *Chapter 5 Section 5.1.1* it summarises the observed synoptic patterns (*Section 2.4.4.1*) categorised by sampling campaign.

2.5.1.2.2. Line plots

Line plots were specifically used to presents data as time series. In *Chapter 2 Section 2.2* it was used to present the annual march, exploring the long term seasonal distribution of surface temperature, relative humidity, and precipitation for the four (4) long term monitoring stations for the climatic period 1981 to 2010 (*see Section 2.4.1.3*). In *Chapter 5 Section 5.1.1* it reflects i) the monthly frequency trend in synoptic circulation patterns observed over the study period (*see Section 2.4.4.1*) and ii) the daily march, exploring the short term differences in surface temperature, relative humidity, and synoptic circulation conditions observer during each sampling campaign (*see Sections 2.4.1.3 and 2.4.4.1*).

2.5.1.2.3. Wind rose plots

Data set six (6) *(see Section 2.4.4.3)* was used to create wind roses for each sampling campaign *(see Table 2.2),* using WRPLOT View™ Version 8.0.2 *(Lakes Environmental Software, 2018)*. Three (3) plot were created for each sampled period which included day-time (06:00-18:00), night-time (18:00-06:00), and a period wind rose plot. This was used to determine seasonal and diurnal wind patterns *(see Chapter 5, Section 0)*. The wind direction was classified into the following sixteen (16) categories N, NNE, NE, ENE,

E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, and NNW. The wind speeds were divided into nine (9) wind classes having increments of 0.5 $m.s^{-1}$ starting from 1 $m.s^{-1}$. Wind speeds below 1 $m.s^{-1}$ were classified as calm conditions. The frequency of occurrence is given in percentage (%).

2.5.1.2.4. Scatter diagrams

Scatter diagrams were specifically used in Chapter 3 Section 3.2.3 and 3.3.3 to investigate the relationship between mass concentration from various photometric instruments *(see Section 2.4.2.2)* and size fractions *(see Section 2.4.2.3)*.

2.5.2. Multivariate statistics

2.5.2.1. Principal component analysis (PCA)

PCA has been applied to particle compositions data *(Jain et al., 2018)*. It aims to reduce the dimensionality of the data in order to identify patterns that point toward similarities and differences that exist in the data *(Jain et al., 2018)* .

The PCA factors were identified using varimax rotation. Factor with an Eigenvalue > 1 were extracted and included in the results. A factors score of 0.5 was selected as the lowest level of significance for the individual elements.

2.6. Ethical principles and considerations

All research was designed and conducted in accordance with North-West University's Policy on Research Ethics *(North-West University, 2018, 2019)*. The individual research projects included in this study had health-related activities, thus had to be ethically cleared by the appropriate Human Research Ethics Council (HREC). The ethical clearance numbers and the relevant HRECs associated with each project is summarised in *Table 2.24*. Research ethics is based on three fundamental principles, namely respect, beneficence, and justice. These principles underpin the ethical considerations related to the research design of this study. These aspects are now discussed in further detail.

Table 2.24 Ethical clearance numbers and HRECs as per research project.

Project Name	Settlement Name	HREC	Ethical Clearance Number
Sasol Offset Pilot	KwaDela	North-West University	NWU-00066-13-A3
Eskom Offset Pilot	KwaZamokuhle	North-West University	NWU-0158-14-S3
PHIRST	Jouberton & Agincourt	University of the Witwatersrand	150808
iDEWS	Giyani	South African Medical Research Council	EC005-3/2014

2.6.1. Community engagement

Community engagement was implemented as a tool to gain the understanding and support of the participating households and communities as a whole. This was primarily achieved by involving the community through local stakeholder representatives. These representatives included a wide spectrum of people such as political leadership (councillors, ward committees, community associations); social leadership (religious leaders, traditional leaders, educators); local- and district government; non-governmental organisations (NGOs); project partners, and project sponsors. This was done so as not to benefit a single group within the community.

2.6.2. Informed consent and anonymity

Prior to data collection, informed consent was obtained for each individual household. The confidentiality of participants are protected as no reference is made to personal information within the study.

2.6.3. Household reimbursement

Households were not paid to participate in these studies, however, reimbursements were offered for the time, inconvenience, and electricity use associated with the monitoring activities within the house. The reimbursement amount was calculated based on the number of electricity consuming instruments placed within each house and the length of time the instrument was assigned to a specific household. This was done so as to not benefit one household above another.

2.6.4. Withdrawal from studies

Participation in the individual studies was entirely voluntary and as such households were allowed to withdraw from the study, without having to state a specific reason. Investigators also retained the right to withdraw a household if it no longer followed the guidelines associated with the specific study.

2.6.5. Risks and benefits

The possible risks and benefits associated with a research project should always be considered before the project commences, this is especially relevant for studies which focus on human health and activities. The environmental monitoring instrumentation used is the study held no risk to the participating households. In some cases the sound made by the instrument pumps could be considered annoying, however, every possible attempt was made to minimise the noise and satisfy the residents within the house. The survey questionnaires did not have any associated risk, however, some of the questions could make participants uncomfortable. The fieldworkers conducting the surveys were trained appropriately and made the questioning as comfortable as possible. There were no direct benefits to the households for their participation in the study. They did, however, receive feedback on the results of the study through community engagement sessions.

2.6.6. Data sharing agreements

Data sharing agreements have been signed with all relevant parties on the use of the data for this study *(see Appendix A)*. These agreements ensure the proper handling and interpretation of the data as described in the data preparation and quality control activities *(see Section 2.4)*.

****

This chapter has outlined the various data acquisition and analysis methodologies used to achieve the objectives set out in *Chapter 1, Section 1.4*. A mixed-method approach was taken and included primarily quantitative experimental data supported by qualitative questionnaire survey data. The laboratory and statistical analysis techniques used to analyse the collected data have been described. It is concluded that the data is representative, reliable and traceable through the systematic approach taken in the research design. The following chapter summarises the weather condition experienced during each of the sampling campaigns conducted between 2013 and 2017.

CHAPTER 3: FIELD EVALUATION OF PHOTOMETRIC INSTRUMENTS

This chapter aims to address the results and discussion surrounding Objective I, as outlined in *Chapter 1, Section 1.4*. The environment in which sampling is undertaken could impact greatly on the performance of the monitoring instruments used. The indoor setting of this study is unique and thus required site-specific field evaluations to ensure that the data are as reliable and representative as possible. There were three areas of concern, namely, i) the accuracy of the PM_4 measurements obtained from the continuous instruments; ii) the comparability of PM_4 measurement recorded by different instrument models; and iii) the particle size fractionation in order to facilitate conversion of PM to different size fractions for air quality standards comparison purposes. These areas of concern were investigated and evaluated through the three collocation studies as described in *Chapter 2, Section 0*.

****

3.1. Photometric calibration factors for PM_4 quantification

The rationale behind this evaluation was to establish photometric calibrations factors (PCFs) for the DustTrak Model 8520 (DT), DustTrak II Model 8530 (DTII), and SidePak AM510 (SP) used in this study. The evaluation was based on collocated continuous and gravimetric PM_4 measurements collected across sixteen (16) sampling campaigns *(see Table 2.10).* These campaigns included one (1) spring, eight (8) summer, and seven (7) winter sampling periods.

Measurements were made in fifty-eight (58) households across the five sampled settlements. Six (6) dwellings were located in the coal-burning communities of KwaDela (4) and KwaZamokuhle (2). Twenty-five (25) houses were situated in the urban community of Jouberton. Twenty-seven (27) of the households were set in rural wood-burning communities of Agincourt (20) and Giyani (7).

The collocated continuous- and gravimetric sampling (2015-2017) resulted in seven-hundred-and-sixty-one (761) 24-hr comparison samples (N). Three-hundred-and-sixteen (316) of which were for the coal-burning communities, while one hundred-and-fifty-six (156) were for the urbanised settlement, and two-hundred-and-eighty-nine (289) were for the wood-burning communities. These collocated measurements

will be discussed further based on the community, settlement, season, household fuel use, and instrument model.

3.1.1. Continuous- and gravimetric PM_4 mass concentrations

The mean (median) ±SD (IQR) [minimum-maximum] 24-hr time-integrated indoor continuous- and gravimetric PM_4 concentrations were 111 (58) ±117 (80) [3-2242] $\mu g.m^{-3}$ and 109 (72) ±143 (82) [4-1447] $\mu g.m^{-3}$, respectively. The coal-burning communities had the highest indoor PM_4 (***Cont.:*** 161 (89) ±210 (141) [12-2242] $\mu g.m^{-3}$; ***Grav.:*** 138 (75) ±182 (91) [8-1447] $\mu g.m^{-3}$) concentrations. These communities were higher by factors of 1.64 and 1.77 than the urbanised community (***Cont.:*** 98 (53) ±151 (58) [7-1282] $\mu g.m^{-3}$; ***Grav.:*** 78 (60) ±70 (73) [4-496] $\mu g.m^{-3}$) and, 2.52 and 1.47 times higher than the wood-burning communities (***Cont.:*** 64 (42) ±133 (43) [3-2091] $\mu g.m^{-3}$; ***Grav.:*** 94 (70) ±117 (79) [5-917] $\mu g.m^{-3}$).

The level of particulate pollution differed from one settlement to the next, regardless of the community type. The concentrations of indoor PM_4 within the five settlements were in the following order: KwaZamokuhle > KwaDela > Giyani > Jouberton > Agincourt. The continuous- and gravimetric PM_4 concentrations in KwaZamokuhle (***Cont.:*** 190 (115) ±241 (182) [12-2242] $\mu g.m^{-3}$; ***Grav.:*** 155 (93) ±170 (120) [8-820] $\mu g.m^{-3}$) were higher by factors ranging from 1.69 to 3.47 and 1.37 to 1.99, respectively, than those recorded in KwaDela (***Cont.:*** 113 (68) ±129 (76) [17-862] $\mu g.m^{-3}$; ***Grav.:*** 109 (62) ±199 (49) [10-1447] $\mu g.m^{-3}$), Jouberton (***Cont.:*** 98 (53) ±151 (58) [7-1282] $\mu g.m^{-3}$; ***Grav.:*** 78 (60) ±70 (73) [4-496] $\mu g.m^{-3}$), Agincourt (***Cont.:*** 55 (40) ±49 (36) [3-439] $\mu g.m^{-3}$; ***Grav.:*** 89 (69) ±100 (77) [5-808] $\mu g.m^{-3}$), and Giyani (***Cont.:*** 98 (50) ±271 (57) [3-2091] $\mu g.m^{-3}$; ***Grav.:*** 113 (73) ±165 (97) [9-917] $\mu g.m^{-3}$).

The seasonally categorised spread of the collocated continuous- and gravimetric PM_4, for each of the five settlements, is given in *Figure 3.1*. The summer concentrations of indoor PM_4 within these settlements were in the following order: KwaDela > Giyani > Jouberton > Agincourt > KwaZamokuhle.

The summer indoor continuous- and gravimetric PM_4 in KwaDela was 2.78 ±1.33 [1.60-4.68] and 1.27 ±0.43 [0.67-1.60] times higher than the other settlements. The winter concentrations of indoor PM_4 within these settlements were in the following order: KwaZamokuhle > Giyani > Jouberton > Agincourt. The winter indoor continuous- and gravimetric PM_4 in KwaZamokuhle was on average 2.53 ±1.25 [1.51-3.92] and 2.81 ±0.94 [2.16-3.89] times higher than the other settlements. The mean winter particulate loadings were always higher than those recorded during the summer. However, in Giyani the highest levels of indoor PM_4 was measured during the spring period (***Cont.:*** 109 (110) ±32 (58) [64-160] $\mu g.m^{-3}$; ***Grav.:*** 136 (141) ±43 (40) [42-185] $\mu g.m^{-3}$). This was followed by the winter (***Cont.:*** 174 (74) ±414 (45) [29-2091] $\mu g.m^{-3}$; ***Grav.:*** 51 (30) ±90 (19) [9-452] $\mu g.m^{-3}$) and then summer (***Cont.:*** 24 (21) ±18 (22) [3-81] $\mu g.m^{-3}$; ***Grav.:*** 163 (81) ±219 (57) [57-917] $\mu g.m^{-3}$). This could be impacted by the relatively small sample size available for the spring (N=8), compared to the summer (N=27) and winter (N=25).

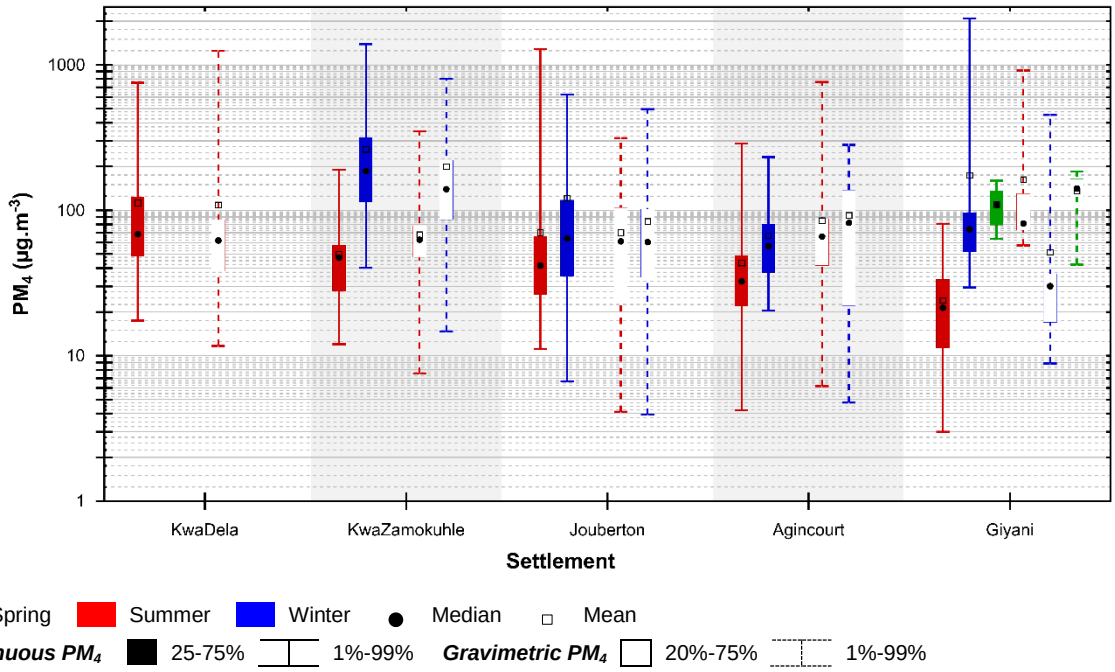


Figure 3.1 Seasonally categorised box-plot of the 24-hr time-averaged continuous- and gravimetric PM_4 concentrations ($\mu g.m^{-3}$) measured in the residential indoor environments within KwaDela, KwaZamokuhle, Jouberton, Agincourt, and Giyani between 2015 and 2017.

Based on the household fuel use classification the collocated continuous- and gravimetric PM_4 were in the following order: indoor solid fuel burning (ISFB) > outdoor solid fuel burning (OSFB) > non-solid fuel burning (NSFB). The indoor continuous- and gravimetric PM_4 in ISFB (***Cont.:*** 139 (79) ±194 (117) [5-2242] $\mu g.m^{-3}$; ***Grav.:*** 136 (80) ±181 (90) [4-1447] $\mu g.m^{-3}$) dwellings was on average 1.71 ±0.59 [1.30-2.13] and 1.57 ±0.17 [1.45-1.69] times higher than the OSFB (***Cont.:*** 66 (40) ±159 (36) [3-2091] $\mu g.m^{-3}$; ***Grav.:*** 94 (63) ±129 (82) [5-917] $\mu g.m^{-3}$) and NSFB (***Cont.:*** 107 (53) ±158 (72) [4-1282] $\mu g.m^{-3}$; ***Grav.:*** 81 (64) ±66 (62) [4-496] $\mu g.m^{-3}$) households. On further classification, by season, the indoor PM_4 concentrations for both the ISFB and NSFB dwelling were in the following order: winter > spring > summer. However, for the OSFB dwellings the order was: spring > winter > summer.

The instrument model is expected to influence the measured mass concentrations. The collocated sampling resulted in one-hundred-and-twenty-six (126), four-hundred-and-forty-four (444), and one-hundred-and-ninety-one (191) time- integrated comparison samples for the DT, DTII, and SP instruments, respectively. Based on the instrument classification the indoor continuous PM_4 were in the following order: DT > SP > DTII. On average, the indoor continuous- and gravimetric PM_4 measured by the DT (***Cont.:*** 166 (59) ±300 (94) [7-2242] $\mu g.m^{-3}$; ***Grav.:*** 116 (79) ±155 (72) [4-788] $\mu g.m^{-3}$) were a factor of 1.86 and 1.99 times higher than the DTII (***Cont.:*** 89 (55) ±140 (60) [3-2090] $\mu g.m^{-3}$; ***Grav.:*** 116 (70) ±121 (34) [4-917] $\mu g.m^{-3}$) measurements. The DT concentrations were also a factor of 1.33 higher and 0.90 lower than those measured by the SP (***Cont.:*** 125 (72) ±132 (114) [12-699] $\mu g.m^{-3}$; ***Grav.:*** 129 (72) ±178 (87) [7-1447] $\mu g.m^{-3}$).

Based on the above mentioned indoor continuous- and gravimetric PM_4 it is expected that the photometric instruments both over-and underestimate the continuous measurements. These over- and underestimations are driven by the Mie-scattering optical properties of particulate aerosols. These properties are impacted by complex factors such as the size distribution, morphology, density and refractive index *(Wallace et al., 2011)* of the particles being measured. The relationship between these two measurements is investigated in more detail as to obtain ratios of over- and underestimation of PM_4 mass concentrations, within the residential indoor environment, for the photometric instruments.

3.1.1.1. Comparison between continuous and gravimetric PM_4 mass concentrations

Ratios were used as an indicator for evaluating the difference between the continuous- and gravimetric PM_4 measured in the residential indoor environment. The photometric instruments overestimate the mass concentration at continuous/gravimetric ratios above one (>1) and underestimate at ratios below one (<1).

The relationship between the 24-hr time-averaged indoor continuous- and gravimetric PM_4 collocated samples (all available samples) is presented in *Figure 3.2*. There is a weak positive correlation (r = 0.33) between the 24-hr continuous- and gravimetric PM_4 results. The linear regression equation was y=67.04+0.41x, with a *p*-value <0.0001. Only 11% (r^2 = 0.11) of the variation in the indoor continuous PM_4 is explained by this linear relationship. The linear regression had a slope of 0.41 and an intercept of 67.04. The mean (median) ±SD (IQR) [minimum-maximum] continuous to gravimetric concentration ratio was 1.70 (0.91) ±2.25 (1.54) [0.01-23.18]. 1

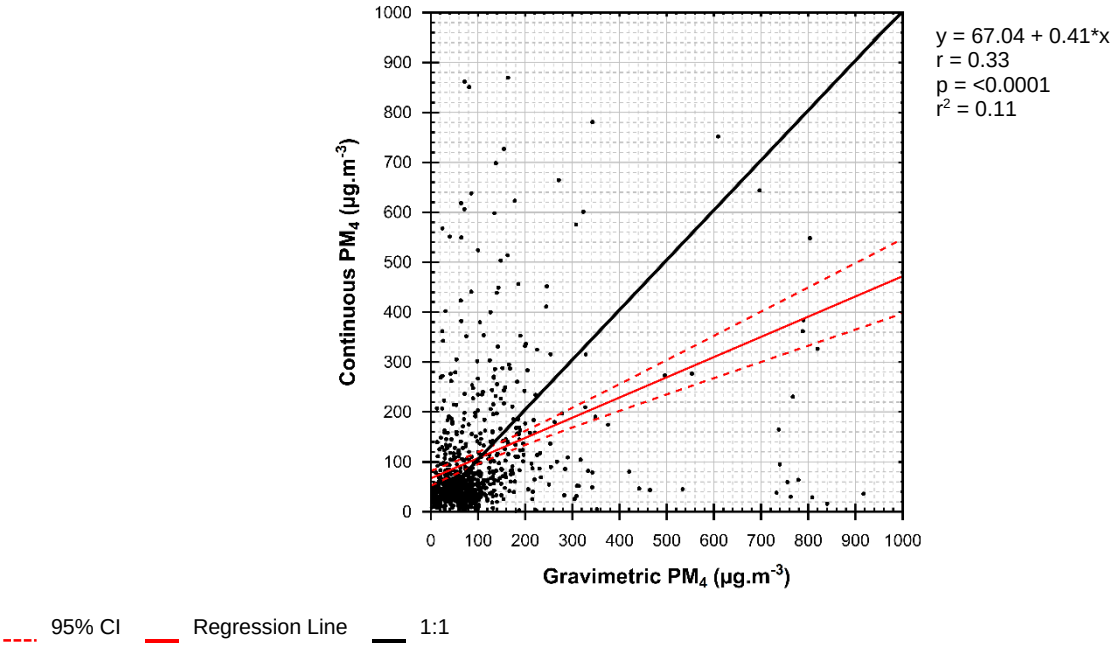


Figure 3.2 Relationship between the 24-hr time-averaged continuous- and gravimetric PM_4 concentrations ($\mu g.m^{-3}$) results (N=761) measured in the residential indoor environments within KwaDela, KwaZamokuhle, Jouberton, Agincourt, and Giyani between 2015 and 2017.

It is expected that the specific micro-environmental setting will impact on the relationship between the indoor continuous- and gravimetric PM_4 concentrations, thus the relationship is further categorised by community, settlement, season, fuel use, and instrument type. The variability in the over- and underestimation of the continuous PM_4 from the photometric instruments is presented in *Figure 3.3* and *Figure 3.4*.

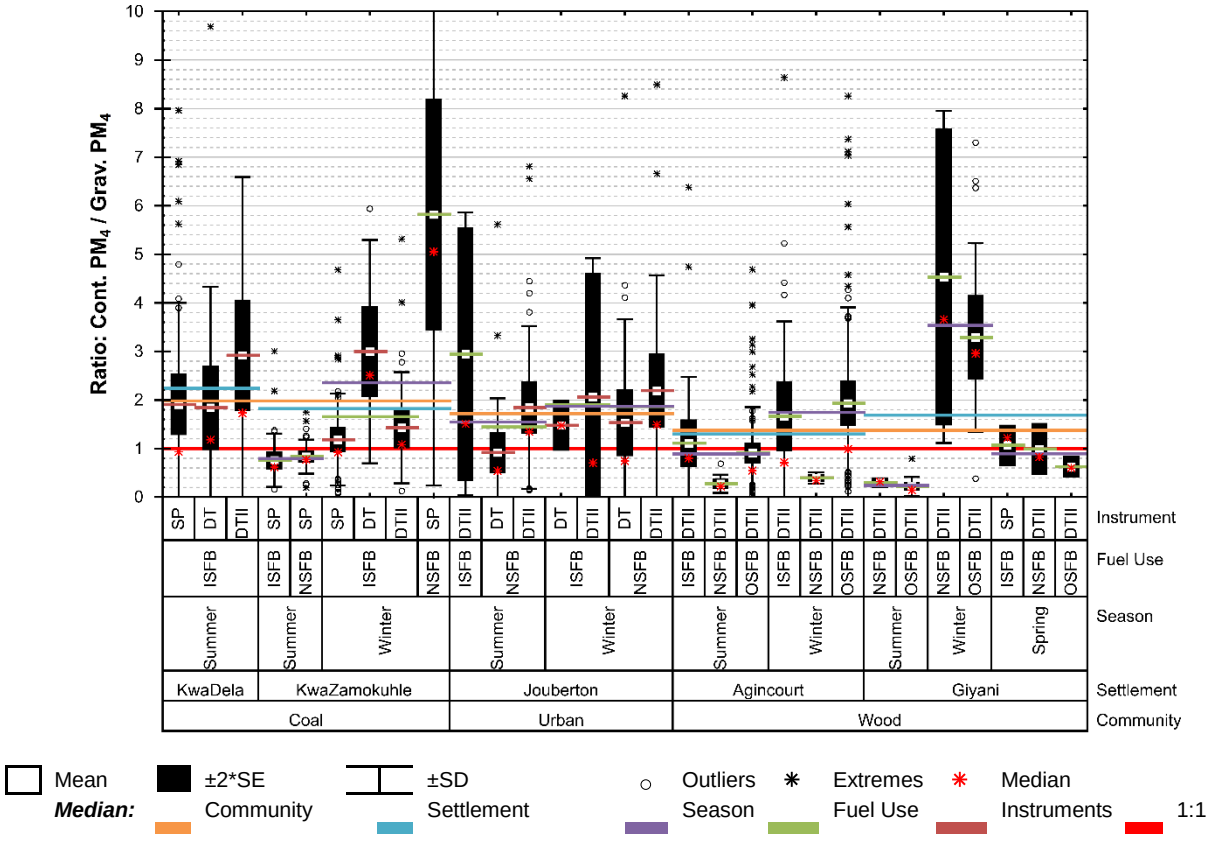


Figure 3.3 Variability box plot of the photometric instrument over- and underestimations ratios of continuous- to gravimetric PM_4 concentrations ($\mu g.m^{-3}$) measured at KwaDela, KwaZamokuhle, Jouberton, Agincourt, and Giyani between 2015 and 2017, categorised by community, settlement, season, fuel use and instrument model.

All three communities experienced mean overestimation of the indoor continuous PM_4 mass concentrations by the photometric instruments. Based on the community classification the ratios of indoor continuous- to gravimetric PM_4 were in the following order: coal > urban > wood. The coal-burning communities (1.98 (1.04) ±2.72 (1.53) [0.08-23.18]) had the highest level of overestimation. This was a factor of 1.15 and 1.43 times higher than the urbanised- (1.72 (1.12) ±2.01 (1.47) [0.13-13.21]) and wood-burning (1.38 (0.69) ±1.72 (1.28) [0.01-10.33]) communities.

The settlement categorised ratios of indoor continuous- to gravimetric PM_4 were in the following order: KwaDela > KwaZamokuhle > Jouberton > Giyani > Agincourt. The coal-burning settlement of KwaDela (2.24 (1.19) ±2.86 (1.79) [0.08-15.19]) had the highest level of overestimation. It was a factor of 1.23

higher than the neighbouring coal-burning settlement of KwaZamokuhle (1.82 (0.94) ±2.63 (1.32) [0.08-23.18]). The overestimation, in the urban settlement of Jouberton, was a factor of 0.77 lower than that of KwaDela. The wood-burning settlement of Agincourt (1.30 (0.69) ±1.58 (1.11) [0.01-8.64]) and Giyani (1.69 (0.65) ±2.14 (1.47) [0.02-10.33]) had the lowest levels of mean overestimation by the photometric instruments. These ratios were a factor 0.58 and 0.75 times lower than KwaDela.

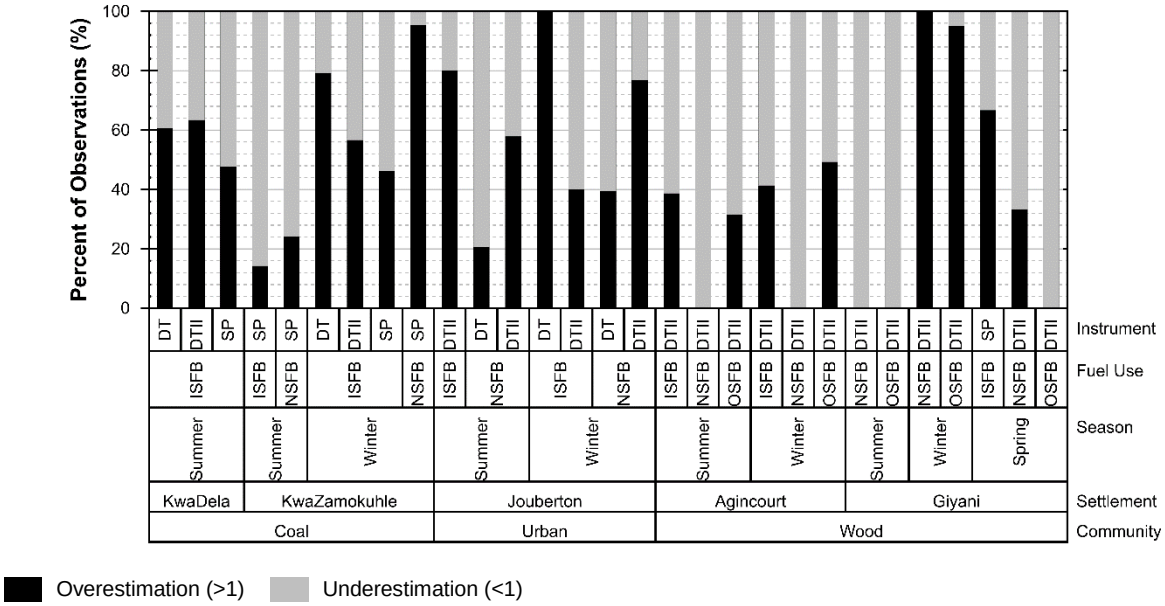


Figure 3.4 Stacked percentage variability plot of the photometric instrument over- and underestimations of PM_4 concentrations measured at KwaDela, KwaZamokuhle, Jouberton, Agincourt, and Giyani between 2015 and 2017, categorised by community, settlement, season, fuel use and instrument model.

Once the seasonal categorisation is considered there is a noteworthy separation in the mean cases of over- and underestimation occurring. The seasonally categorised ratios of indoor continuous- to gravimetric PM_4 were in the following order: winter > summer > spring. Winter had a mean overestimation ratio of 2.13 (1.30) ±2.56 (1.91) [0.5-23.18], which was 1.59 and 2.39 times higher than summer (1.34 (0.73) ±1.91 (1.03) [0.01-15.19]) and spring (0.89 (0.82) ±0.37 (0.59) [0.45-1.51]) ratios.

There were six (6) mean cases of overestimation with ratios ranging between 1.55 and 3.54. Two (2) of these cases were for the summer, which included the settlement of KwaDela (2.24 (1.19) ±2.86 (1.79) [0.08-15.19]) and Jouberton (1.55 (1.66) ±1.26 (2.12) [0.14-7.83]). Four (4) of the cases were for the winter, which included the settlements of KwaZamokuhle (2.36 (1.49) ±3.10 (2.07) [0.08-23.18]), Jouberton (1.87 (1.22) ±2.26 (1.21) [0.13-13.21]), Agincourt (1.74 (0.83) ±1.93 (1.85) [0.05-8.64]), and Giyani (3.54 (3.02) ±2.28 (2.69) [0.38-10.33]). Thus, all individual winter campaigns showed a mean overestimation of indoor continuous PM_4 by the photometric instruments.

There were our (4) mean cases of underestimation with ratios ranging between 0.24 and 0.89, with three (3) being summer cases and a single (1) spring case. The summer cases included the settlements of

KwaZamokuhle (0.79 (0.72) ±0.46 (0.38) [0.16-3.00]), Agincourt (0.89 (0.53) ±1.04 (0.83) [0.01-6.38]), and Giyani (0.24 (0.22) ±0.18 (0.27) [0.02-0.79]). The spring case of underestimation occurred in Giyani (0.89 (0.82) ±0.37 (0.59) [0.45-1.51]). This case was similar to that of Agincourt during the summer.

Based on the household fuel use classification the ratios of indoor continuous- to gravimetric PM_4 were in the following order: NSFB > ISFB > OSFB. The NSFB (1.83 (0.85) ±1.73 (1.38) [0.07-23.18]) ratios being 1.06 and 1.25 times higher than the ISFB (1.74 (1.00) ±2.15 (1.52) [0.01-15.19]) and OSFB (1.46 (0.77) ±1.71 (1.42) [0.01-8.26]) households.

There were three (3) cases of mean overestimation within the coal-burning communities, one (1) during the summer (KwaDela) and two (2) winter (KwaZamokuhle). These were recorded within the ISFB dwellings in KwaDela (2.24 (1.19) ±2.86 (1.79) [0.08-15.19]) and KwaZamokuhle (1.65 (1.11) ±1.57 (1.47) [0.08-10.47]), as well as the NSFB households in KwaZamokuhle (5.82 (5.06) ±5.58 (5.77) [0.83-23.18]). The NSFB household experienced the highest level of overestimation during the winter.

There were two (2) cases of underestimation within the coal-burning communities, both occurring during the summer. These were recorded within the ISFB (0.76 (0.62) ±0.55 (0.46) [0.16-3.00]) and NSFB (0.83 (0.77) ±0.35 (0.29) [0.19-1.75]) households in KwaZamokuhle. The ISFB households had the highest level of underestimation during the summer.

The urbanised community of Jouberton experienced four (4) cases of overestimation, two (2) during both summer and winter, respectively. The ISFB (2.95 (1.51) ±2.91 (2.32) [0.83-7.83]) households experienced higher levels of overestimation, during the summer, compared to the NSFB 1.44 (0.80) ±1.53 (1.68) [0.14-6.81] dwellings. This is also true for the winter, however, the ratios for the ISFB (1.90 (1.21) ±2.36 (1.06) [0.57-7.16]) and NSFB (1.87 (0.80) ±1.53 (1.68) [0.14-6.81]) dwellings were closer than those recorded during summer. There were no cases of mean underestimation when considering just community, settlement, season, and solid fuels use.

There were six (6) cases of mean overestimation within the wood-burning communities. One (1) case each during spring (Giyani) and summer (Agincourt), respectively. The majority of the cases occurring in winter with two (2) cases each in Agincourt and Giyani. The ISFB dwellings in Agincourt had summer and winter ratios of 1.11 (0.80) ±1.36 (0.82) [0.01-6.38] and 1.66 (0.71) ±1.96 (1.91) [0.05-8.64], respectively. The ISFB household in Giyani experienced ratios close to unity (1.07 (1.22) ±0.37 (0.68) [0.65-1.33]) during spring. The winter ratios for the NSFB dwellings in Giyani had a mean winter ratio of 4.53 (3.66) ±3.42 (1.41) [1.42-10.33]. The OSFB households in Agincourt and Giyani had winter ratios of 1.93 (0.99) ±1.98 (2.06) [0.12-8.26] and 3.29 (2.96) ±1.95 (2.90) [0.38-7.30], respectively.

The wood-burning communities experienced seven (7) cases of mean underestimation of the indoor continuous PM_4 concentrations by the photometric instruments. This includes two (2) spring, four (4)

summer, and a single (1) winter cases. The NSFB dwellings in Agincourt had summer and winter ratios of (0.27 (0.22) ±0.19 (0.21) [0.07-0.69]) and (0.39 (0.34) ±0.12 (0.19) [0.30-0.60]), respectively. The NSFB households in Giyani had a similar mean summer ratio (0.29 (0.32) ±0.09 (0.14) [0.14-0.42]) to that of Agincourt, while the spring ratio was close to unity (0.99 (0.82) ±0.46 (0.88) [0.64-1.51]). The OSFB dwellings in Agincourt and Giyani had a summer ratio of (0.91 (0.55) ±0.95 (0.95) [0.01-4.69]) and (0.22 (0.15) ±0.20 (0.28) [0.02-0.79]), respectively. The OSFB household in Giyani had a lower ratio of underestimation during spring (0.63 (0.60) ±0.20 (0.39) [0.45-0.83]).

Finally, the photometric instrument model is considered. Based on this the mean ratios for indoor continuous- to gravimetric PM_4 were in the following order: DT > SP > DTII. All three instrument models experienced mean overestimation of the continuous PM_4 mass concentrations. The DT (1.75 (0.99) ±2.16 (1.50) [0.08-12.04]) and SP (1.74 (0.87) ±2.67 (1.13) [0.08-23.18]) instrument had similar ratios of overestimation. The DT and SP ratios were 1.05 times higher than those of the DTII (1.66 (0.91) ±1.08 (1.67) [0.01-15.19]) instrument model.

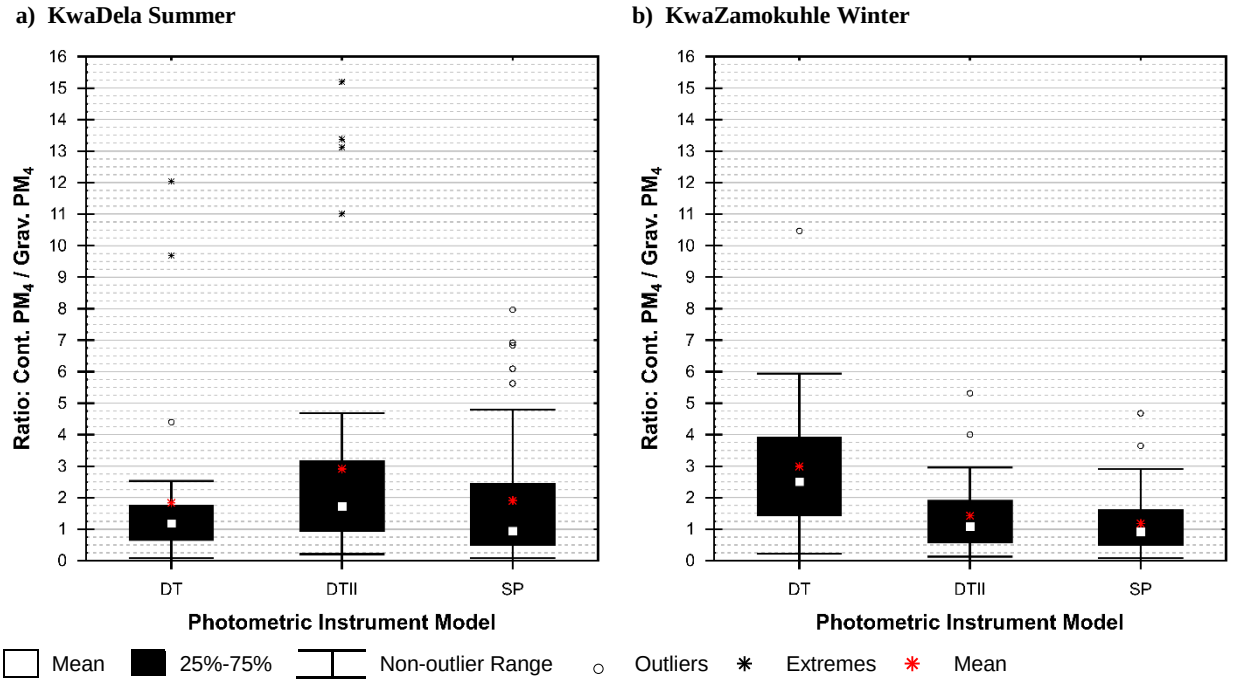


Figure 3.5 Box plot of the ratios of continuous- to gravimetric PM_4 concentrations ($\mu g.m^{-3}$) measured in the ISFB household in a) KwaDela summer and b) KwaZamokuhle winter, categorised by instrument model.

All three instrument models were used within the ISFB household in the coal-burning communities of KwaDela (summer) and KwaZamokuhle (winter). Even though the conditions were similar for both the households in this comparison, there is a definite difference in the seasonal performance of the different instrument models *(Figure 3.5 a & b)*. During summer and winter the mean ratios for indoor continuous- to gravimetric PM_4 were in the following order: DTII > SP > DT and DT > DTII > SP, respectively. The

mean overestimation ratio of DT during summer (1.84 (1.18) ±1.50 (1.13) [0.08-12.04]) was a factor of 0.61 lower than during the winter (3.00 (2.51) ±2.30 (2.51) [0.22-10.47]). The opposite was true for the DTII (***Summer:*** 2.92 (1.73) ±3.67 (2.26) [0.21-15.19]; ***Winter:*** 1.43 (1.09) ±1.14 (1.36) [0.13-5.32]) and SP (***Summer:*** 1.91 (0.94) ±2.09 (1.98) [0.08-7.91]; ***Winter:*** 1.18 (0.93) ±0.95 (1.14) [0.08-4.68]) instrument models. The mean overestimation ratios during summer were a factor of 2.05 and 1.61 higher than during the winter.

These over- and underestimation ratios, as well as the associated photometric calibration factor (PCFs) results, are compared to previously published studies in the flowing sections.

3.1.2. Calculated PCFs vs previously published studies

Based on the previously discussed relationship between the indoor continuous- and gravimetric PM_4 a wide range of PCFs are expected. The residential indoor PM_4 PCFs were calculated based on the mean ratios of over-and underestimation, which were categorised by community, settlement, season, household solid fuel use, and instrument model *(Table 3.1)*. A PCF below one (<1) indicates that the initial continuous PM_4 will be reduced due to overestimation. A PCF above one (>1) point toward an increase in the initial continuous PM_4 due to underestimation.

The mean (median) ±SD (IQR) [minimum-maximum] PM_4 PCF for the residential indoor environment is 1.09 (0.68) ±1.09 (0.61) [0.17-4.52]. Based on the community categories the PCFs were in the following order: urban < coal < wood. The coal-burning and urban communities had similar mean PCF of 0.66 (0.54) ±0.39 (0.50) [0.17-1.32] and 0.61 (0.54) ±0.24 (0.22) [0.34-1.09], respectively. The wood-burning communities had the highest mean PCF at 1.64 (1.01) ±1.42 (1.93) [0.22-4.52], which indicated the highest level of underestimation by the photometric instruments.

The settlement categorised mean PM_4 PCF for the residential indoor environment were in the following order: KwaDela < Jouberton < KwaZamokuhle < Agincourt < Giyani. KwaDela (0.47 (0.52) ±0.11 (0.20) [0.34-0.54]) had the lowest mean PCF coal-burning settlements, followed by KwaZamokuhle (0.76 (0.77) ±0.46 (0.87) [0.17-1.31]). The mean PCF for the urban settlement of Jouberton (0.61 (0.54) ±0.24 (0.22) [0.34-1.09]) was closer related to those calculated for the coal-burning settlement than to the wood-burning settlement. Agincourt (1.55 (1.00) ±1.27 (1.93) [0.52-3.66]) had a lower mean PCF compared to that of Giyani (1.72 (1.01) ±1.64 (3.11) [0.22-4.52]).

The seasonally categorised mean PM_4 PCF for the residential indoor environment were in the following order: winter < spring < summer. This links to the higher levels of overestimation which occurred during the winter periods. The mean PCF for spring (1.18 (1.01) ±0.36 (0.66) [0.94-1.60]) is closer related to that calculated for summer (1.50 (1.09) ±1.41 (0.78) [0.34-4.52]) than for winter (0.65 (0.52) ±0.61 (0.34) [0.17-2.54]).

Table 3.1. Over- and underestimation ratios and associated residential indoor PM_4 PCFs for DT, DTII, and SP instruments, categorised by community, settlement, season, and solid fuel use.

Community	Settlement	Season	Fuel Use	Instrument Model	Continuous- to Gravimetric PM_4 Ratio	Indoor PM_4 PCF
Coal	KwaDela	Summer	ISFB	DT	1.84	0.54
				DTII	2.92	0.34
				SP	1.91	0.52
	KwaZamokuhle	Summer	ISFB	SP	0.76	1.32
			NSFB	SP	0.83	1.20
		Winter	ISFB	DT	3.00	0.33
				DTII	1.43	0.70
				SP	1.18	0.85
			NSFB	SP	5.82	0.17
Urban	Jouberton	Summer	ISFB	DTII	2.95	0.34
			NSFB	DT	0.92	1.09
				DTII	1.85	0.54
		Winter	ISFB	DT	1.48	0.68
				DTII	2.06	0.48
			NSFB	DT	1.53	0.65
				DTII	2.19	0.46
Wood	Agincourt	Summer	ISFB	DTII	1.11	0.90
			NSFB	DTII	0.27	3.66
			OSFB	DTII	0.91	1.10
		Winter	ISFB	DTII	1.66	0.60
			NSFB	DTII	0.39	2.54
			OSFB	DTII	1.93	0.52
	Giyani	Spring	ISFB	SP	1.07	0.94
			NSFB	DTII	0.99	1.01
			OSFB	DTII	0.63	1.60
		Summer	NSFB	DTII	0.29	3.41
			OSFB	DTII	0.22	4.52
		Winter	NSFB	DTII	4.53	0.22
			OSFB	DTII	3.29	0.30

Note: ISFB = indoor solid fuel burning; **NSFB =** non-solid fuel burning; **OSFB =** outdoor solid fuel burning; **DT =** DustTrak 8520; **DTII =** DustTrak 8530; **SP =** SidePak

The household fuel use categorised mean PM_4 PCF for the residential indoor environment were in the following order: ISFB < NSFB < OSFB. The ISFB dwellings had the lowest mean PCF at 0.66 (0.60) ±0.29 (0.36) [0.33-1.32] and are also the only to show a mean overestimation of the continuous PM_4 measurements. Both the NSFB- (1.36 (1.01) ±1.26 (2.08) [0.17-3.66]) and OSFB (1.61 (1.10) ±1.71 (1.08)

[0.30-4.52]) households had mean PCFs associated with underestimation of the continuous PM_4 measurements by the photometric instruments.

Based on the photometric instrument model categories the mean PM_4 PCF for the residential indoor environment were in the following order: DT < SP < DTII. The older model DT (0.66 (0.65) ±0.28 (0.13) [0.33-1.09]) had the lowest mean PCF. The DT PCF was a factor of 0.51 and 0.79 lower than those calculated for the newer model DTII (1.29 (0.65) ±1.32 (1.14) [0.22-4.52]) and SP (0.83 (0.89) ±0.43 (0.68) [0.17-1.32]).

The photometric calibrations factors (N=40) available in the literature have been summarised in *Table 3.2* with regard to the size fraction ($PM_{2.5}$ or PM_{10}), type of aerosol (ambient or indoor), environment (urban, rural, or laboratory), and various micro-environment.

There is a definite variability in the range of PCFs that have been determined over the years by different investigators *(Figure 3.6)*. These included only the $PM_{2.5}$ (N=28) and PM_{10} (N=12) size fraction, as there were no PCFs available for the respirable (PM_4) fractions within the literature.

Table 3.2. Overestimation ratios and photometric calibration factors for DT, DTII, and SP instruments categorised by PM size fraction, type, environment, and micro-environment *(adapted from TSI Incorporated, 2013)*.

Source	Ratio	Cal. Factor	PM Fraction	Type	Env.	Micro-environment	Instrument
(Braniš & Hovorka, 2005)	2.34	0.43*	2.5	A	U	Urban centre	DT
	2.12	0.47*	2.5	I	U	Urban centre	DT
	3.91	0.26*	2.5	A	U	Urban centre	DT
	3.29	0.30*	2.5	I	U	Urban centre	DT
	4.02	0.25*	2.5	A	U	Urban background	DT
	3.37	0.30*	2.5	I	U	Urban background	DT
	3.12	0.32*	10	A	R	Rural village	DT
	2.49	0.40*	10	A	R	Rural village	DT
	3.2	0.31*	10	A	U	Urban background	DT
	1.27	0.79*	10	A	U	Urban centre	DT
	1.93	0.52*	10	A	U	Urban centre	DT
(Chung et al., 2001)	3.00	0.33*	10	A	U	Urban centre	DT
(Heal et al., 2000)	2.20	0.45*	10	I	U	Unoccupied room	DT
(Kingham et al., 2006)	2.73	0.37*	10	A	U	Wood smoke	DT

Table 3.2 (Continued)

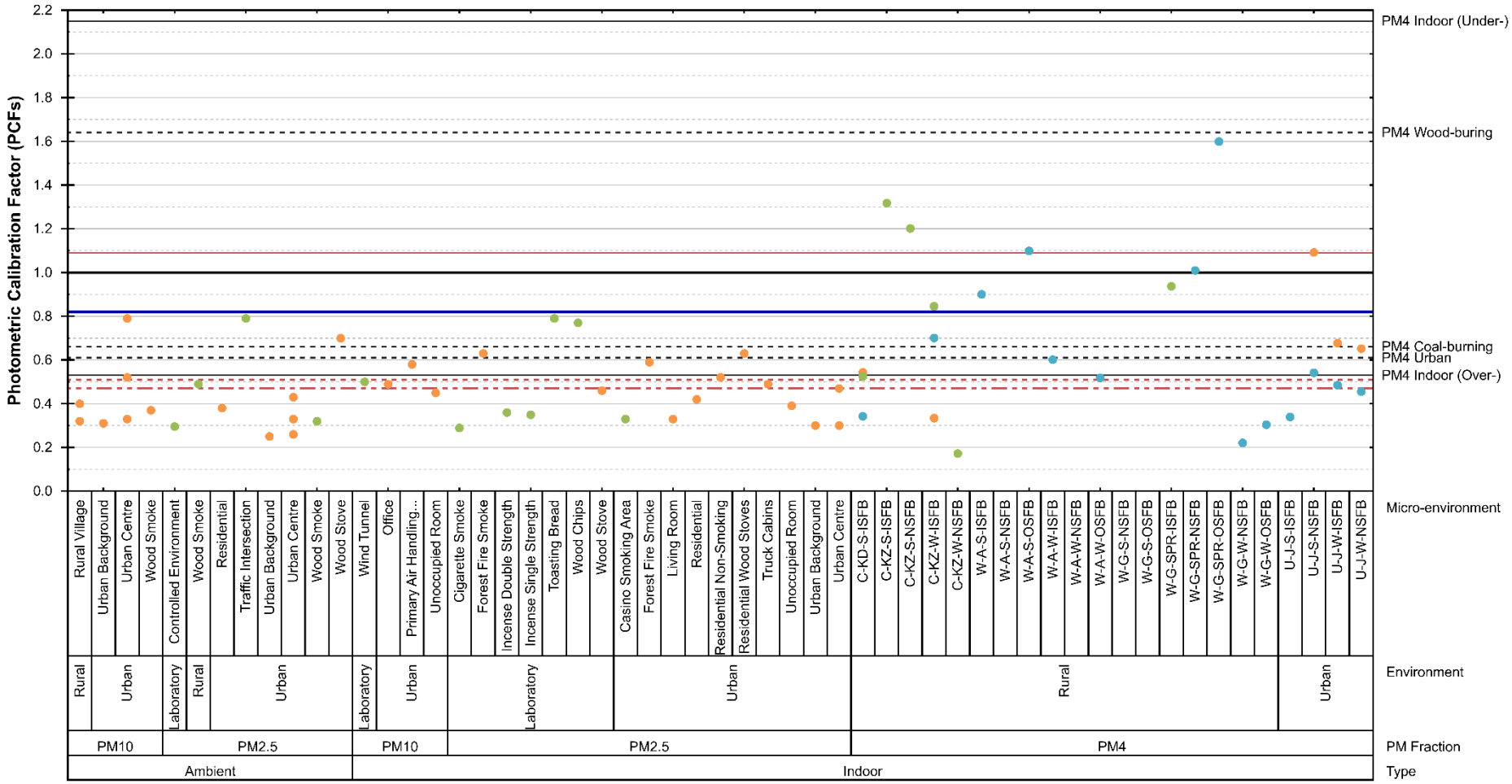
Source	Ratio	Cal. Factor	PM Fraction	Type	Env.	Micro-environment	Instrument
(McNamara et al., 2011)	2.18	0.46*	2.5	I	L	Wood stove	DT
	1.59	0.63*	2.5	I	L	Forest fire smoke	DT
	1.7	0.59*	2.5	I	U	Forest fire smoke	DT
	1.60	0.63*	2.5	I	U	Residential wood stoves	DT
	1.43	0.70*	2.5	A	U	Wood stove	DT
(Niu et al., 2002)	2.04	0.49*	10	I	U	Office	DT
	1.73	0.58*	10	I	U	Primary air handling room	DT
(Ramachandran et al., 2000)	2.99	0.33*	2.5	A	U	Urban centre	DT
	1.94	0.52*	2.5	I	U	Residential non-smoking	DT
(Wallace et al., 2011)	2.39	0.42*	2.5	I	U	Residential	DT
	2.64	0.38*	2.5	A	U	Residential	DT
(Yanosky et al., 2002)	2.59	0.39*	2.5	I	U	Unoccupied room	DT
(Zhu et al., 2011)	2.04	0.49*	2.5	I	U	Truck cabins	DT
(Jiang et al., 2011)	3.40**	0.29	2.5	I	L	Cigarette smoke	SP
	2.80**	0.36	2.5	I	L	Incense double strength	SP
	2.85**	0.35	2.5	I	L	Incense single strength	SP
	1.30**	0.77	2.5	I	L	Burning wood chips	SP
	1.27**	0.79	2.5	I	L	Toasting bread	SP
	1.27**	0.79	2.5	A	U	Traffic intersection	SP
	3.00	0.33	2.5	I	U	Casino smoking area	SP
	2.06**	0.49	2.5	A	R	Wood smoke	SP
	3.10**	0.32	2.5	A	U	Wood smoke	SP
(Thorpe, 2007)	2.00	0.5*	10	I	L	Wind tunnel	SP
(Zhu et al., 2007)	3.40	0.29*	2.5	A	L	Controlled Facility	SP
(Osman et al., 2007)	3.00	0.33*	2.5	I	U	Living room	DT

*** Calibration factor calculated from given ratio**

**** Ratio calculated from given calibration factor**

A – Ambient I – Indoor U – Urban R – Rural L - Laboratory

Investigating only the PCFs from literature the mean PCF, regardless of PM type, size fraction, and environment categories, is 0.45 (0.42) ±0.16 (0.19) [0.25-0.79]. On average, the ambient (0.43 (0.37) ±0.17 (0.17) [0.25-0.79]) environment PCF was a factor of 0.90 lower than that of the indoor (0.48 (0.47) ±0.14 (0.23) [0.29-0.79]) environment. The mean PCFs for the $PM_{2.5}$ (0.45 (0.41) ±0.17 (0.23) [0.25-0.79]) and PM_{10} (0.46 (0.47) ±0.14 (0.17) [0.31-0.79]) size fraction were similar.



Note: **C** = coal-burning; **U** = urban; **W** = wood-burning; **KD** = KwaDela; **KZ** = KwaZamokuhle; **J** = Jouberton; **A** = Agincourt; **G** = Giyani; **SPR** = spring; **S** = summer; **W** = winter; **ISFB** = indoor solid fuel burning; **NSFB** = non-solid fuel burning; **OSFB** = outdoor solid fuel burning

DT DTII SP ***Indoor Means:*** Overall PM2.5 PM10 PM4

Figure 3.6 Variability plot of photometric calibration factors (PCFs) within literature (PM_{10} & $PM_{2.5}$) and the current study (PM_4) categorised by type, size fraction, environment, micro-environment, and instrument.

Once the environmental classification is considered there is a noteworthy separation in the mean PCFs that occur. The rural (0.40 (0.40) ±0.09 (0.17) [0.32-0.49]) environments had the lowest mean PCF, indicating the highest level of overestimation. The urban (0.45 (0.42) ±0.15 (0.19) [0.25-0.79]) environment had had mean PCFs that were a factor of 1.11 higher than the rural settings. The laboratory (0.49 (0.46) ±0.19 (0.28) [0.29-0.79]) setting had the highest mean PCFs. This could possibly be linked to the controlled nature of laboratory experiments. Considering the photometric instrument model, the DT (0.45 (0.43) ±0.14 (0.19) [0.25-0.79]) had lower mean PCFs than the SP (0.48 (0.36) ±0.21 (0.45) [0.29-0.79]). This was supported by the instrument model findings for the PM_4 size fraction made in the current study. There is even more separation in the calculated PCFs when the specific micro-environment are considered.

The mean PCFs calculated in this study are within the range of others reported in the literature, however, this study included mean cases of underestimation which was not present in the literature. The above categorisation provides a relatively good representation of the mean PM_4 PCF for the residential indoor environment within the various low-income settlement in South Africa. However, due to the high variability that exists it is recommended that a combination of all five categories of classification is used to determine the appropriate PCFs for this study. One could still consider using a category-specific PCF, however, it is important to consider the impact of this on the data set as whole. Should an overestimation PCF be applied to a dataset containing episodes of both over-and underestimation, the data could be negatively influenced, as underestimated values are reduced even more. The same logic pertains to a dataset to which an underestimation PCF is applied as it will increase already overestimated values. The PCFs could be influenced by various aspects and differs from one environment to the next. Thus, it has implications for generalising the results towards the community or even using it for other similar communities in the region.

3.2. Photometric instrument comparison of PM_4 mass concentrations

The rationale behind this evaluation was to investigate the comparability between the various models of photometric instruments. This evaluation was based on collocated PM_4 DustTrak Model 8520 (DT), DustTrak II Model 8530 (DTII), and SidePak AM510 (SP) measurements collected during two (2) sampling periods nested within campaigns 5 and 7 *(see Table 2.2)*, covering a summer and winter period within H024 situated in KwaZamokuhle. The household is classified as an ISFB house which used coal within the indoor environment during winter for both cooking and heating (none during summer). A full description of the house is given in *Section 2.3.2.3.3*.

3.2.1. Temporal trends in PM_4 for DT, DTII, and SP instruments

The temporal trend of the 5-min averaged DT, DTII, and SP PM_4 concentrations measured in H024 during the summer and winter are given in *Figure 3.7 a* and *b*, respectively. The peaks throughout the time-series

are consistent for all three instruments, however, the DT instrument had higher baseline concentrations during the first half of the winter measurements *(Figure 3.7.b)*. The discrepancy could be related to the initial zeroing of the instrument which is expected to impact the agreement and comparability of the instruments. The peaks in mass concentration are also well represented by the different instrument, however, during the winter, the DT shows significantly higher peaks than the DT II and SP instruments. These high concentrations are linked back to the level of overestimation calculated in *Section 3.1.2 (see Table 3.1)* where the ratios indicated overestimation factors of 3.00, 1.43, and 1.18, respectively for the DT, DTII, and SP situated in the indoor solid fuel-burning house H024.

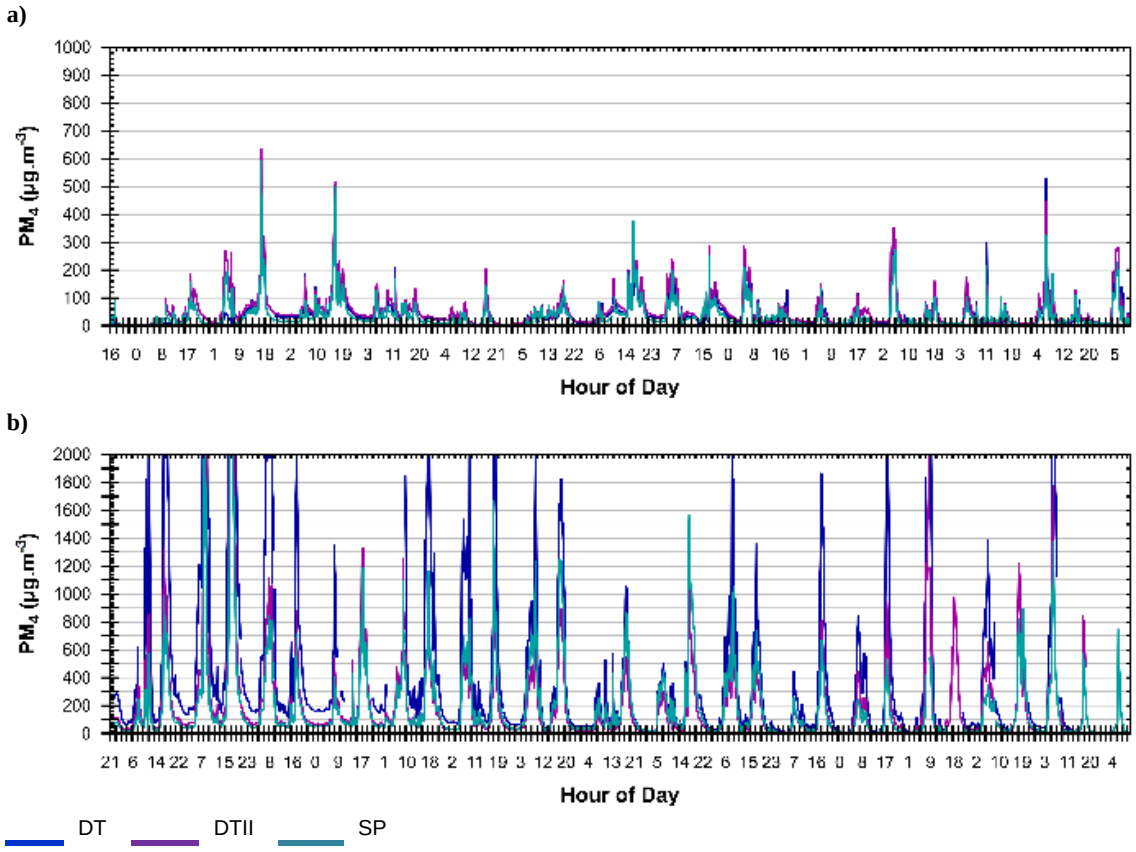


Figure 3.7 Time series of 5-min averaged collocated DT, DTII, and SP PM_4 concentrations ($\mu g.m^{-3}$) measured in KwaZamokuhle at H024 during a) summer (22 February to 7 March 2016) and b) winter (6 to 22, July 2015).

3.2.2. PM_{10}, PM_4, $PM_{2.5}$ and PM_1 mass concentrations

The DT, DTII, and SP PM_4 concentrations were measured in H024 for a period of fourteen (14) and sixteen (16) days, respectively, from 22 February to 7 March 2016 (summer) and 6 to 22 Jul 2015 (winter). The above sampling resulted in the collection of 23 526 individual data points of which 11 416 (3 604, 3 904, and 3 908 for the DT, DTII, and SP) were recorded during summer and 12 110 (3 664, 4 170, 4 276 for the DT, DTII, and SP) in winter. Cases that did not have valid data points for all three instruments were excluded, resulting in 3 539 and 3 603 valid comparison cases for summer and winter, respectively. This

indicates a data retrieval rate ranging between 84.3 and 98.3 %. A summary of the overall descriptive statistics, for the collocated evaluation period, is given in *Table 3.3*.

Table 3.3 Descriptive statistics for 5-min collocated DT, DTII, and SP PM_4 (µg.m^{-3}) categorised by season.

Season		**Summer**			**Winter**		
Instrument		**DT**	**DTII**	**SP**	**DT**	**DTII**	**SP**
Mean		37.5	49.4	31.4	464.9	193.4	178.2
(±95%CI)		(36.0-39.0)	(47.14-51.3)	(30.0-32.8)	(429.1-500.8)	(179.4-207.4)	(167.3-189.2)
±SD		46.7	59.0	42.8	1098.1	419.0	328.0
(±95%CI)		(45.6-48.8)	(57.7-60.4)	(41.8-43.8)	(1073.3-1124.1)	(419.0-438.8)	(328.8-344.3)
Std. Err.		0.8	1.0	0.7	18.3	7.1	5.6
Min		0.0	2.0	0.0	7.0	0.0	0.0
Percentiles	**1st**	2.0	2.0	0.0	9.0	2.0	1.0
	25th	10.0	14.0	7.0	68.0	29.0	33.0
	Median	23.0	32.0	17.0	173.0	73.0	65.0
	75th	45.0	59.0	37.0	420.0	197.0	192.0
	99th	229.0	285.5	203.0	4552.0	1780.0	1419.0
Max		528.0	513.0	500.0	18201.0	6250.0	4864.0

Note: ±SD = standard deviation of mean**; Std. Err.** = Standard error of the mean; **±95% CI** = confidence interval

The PM_4 concentrations *(Table 3.3)* during summer for the DT, DTII, and SP ranged up to a maximum of 528.0, 521.0, and 500.0 µg.m^{-3}, respectively, with means (±SD) of 37.5 (±46.7), 49.4 (±59.0), and 31.4 (±42.8) µg.m^{-3}. The ratios of the maximum concentration were close to unity indicating that the instruments recorded similar extreme values during the summer. The ratios of the mean PM_4 concentrations indicated that the DT had a lower measured PM_4 concentration (factor of 0.75) compared to the DTII. The DT and DTII instruments had higher (factor of 1.57 and 1.19) mean PM_4 concentrations compared to the SP.

The winter PM_4 concentrations show similar trends with the DT (18 201.0 µg.m^{-3}) having the highest maximum followed by the DTII (6 250.0 µg.m^{-3}) and SP (4 864.0 µg.m^{-3}) instruments. The winter means were 464.9 (±1 098.1), 193.4 (±419.0), and 178.2 (±328.0) µg.m^{-3}, respectively. The ratios of the maximum concentrations indicated that the DT recorded more extreme maximums (factor of 2.91 and 3.74) compared to the DTII and SP instruments. The DTII maximum PM_4 concentration was a factor of 1.28 higher than the SP, indicating a better relationship between the DTII and SP models of the photometric instruments. The rations of the mean PM_4 concentrations showed an improved relationship as the DT was higher than the DTII and SP by factors of 2.40 and 2.61, respectively. The DTII and SP mean concentrations had a ratio close to unity (0.92).

The frequency distribution, in percentage (%), of the recorded 5-min averaged raw PM_4 mass concentrations for each instrument during summer and winter is given in *Figure 3.8 a* and *b*. During the

winter *(Figure 3.8.b)* ~24% of the recorded measurements are above 200 µg.m^{-3} for both the DTII and SP, however, for the DT, it is ~45%. This increased percentage of measurements above 200 µg.m^{-3} for the DT, when compared to the DTII and SP, could indicate that the older DT model overestimates mass concentration by a factor of two higher than the DTII and SP within a micro-environment where high PM mass concentrations exist. At lower mass concentrations during the summer *(Figure 3.8.a)*, this does not seem to be a problem as the percentages range between ~1 and 4% for the different instruments.

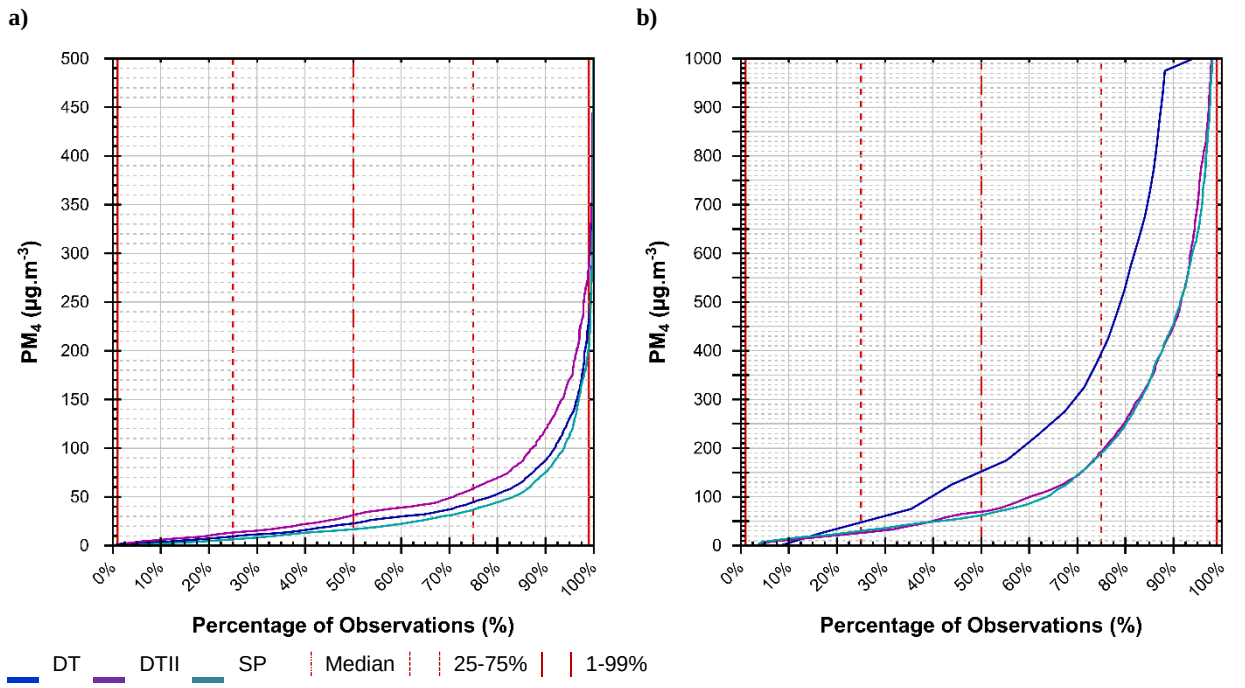


Figure 3.8 Cumulative frequency distribution (%) for 5-min averaged collocated DT, DTII, and SP PM_4 concentrations (µg.m^{-3}) during a) summer and b) winter.

3.2.3. Comparison between PM_4 for DT, DTII, and SP instruments

The relationship between the initial indoor PM_4 mass concentrations for the DT, DTII, and SP photometric instruments are presented in *Figure 3.9 a* and *b* for summer and winter, respectively.

There is a good agreement between the indoor PM_4 mass concentrations from the DT, DTII and SP instruments for the summer period *(Figure 3.9.a)*. There is a very good positive correlation (r = 0.92) between the DT and DTII 5-min averaged measurements. The linear regression equation was y = 5.80 + 1.16*x, with a p-value <0.0001. The linear regression had a slope of 1.16 and an intercept of 5.79. Approximately 85% (r^2 = 0.85) of the variation is explained by this relationship. Similarly, there is very good agreement (r = 0.92) between the DT and SP 5-min averaged measurements. The linear regression equation was y = -0.01 + 0.8*x, with a p-value <0.0001. The linear regression had a slope of 0.84 and an intercept of -0.01. Approximately 84% (r^2 = 0.84) of the variation is explained by this relationship.

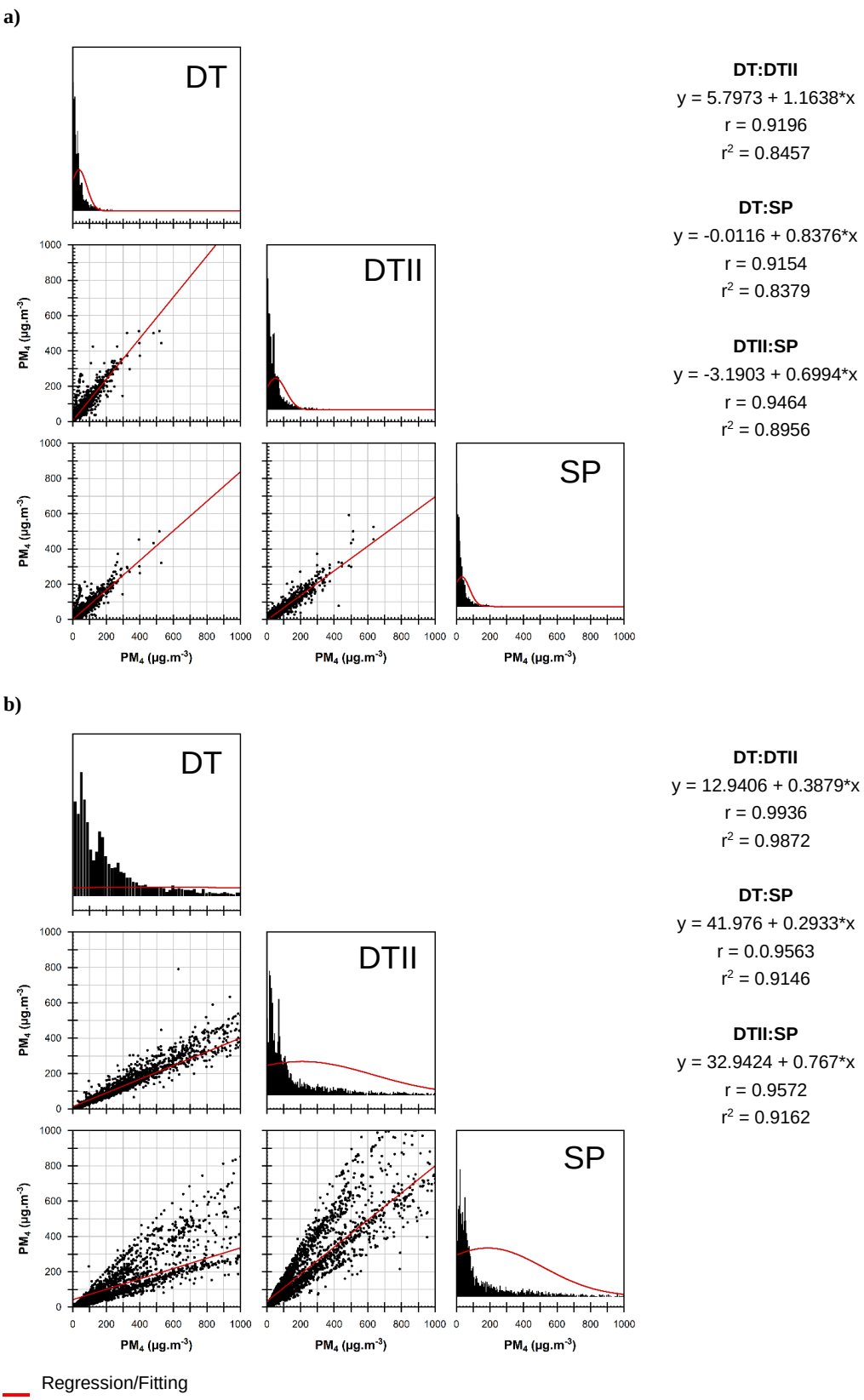


Figure 3.9 Scatterplot of 5-min averaged collocated DT, DTII, and SP indoor PM_4 concentrations ($\mu g.m^{-3}$) measured at H24 in KwaZamokuhle from a) 22 February to 7 March July 2016 (summer) and b) 6 to 22 July 2015 (winter).

The DTII and SP showed the best agreement (r = 0.95) between its 5min averages measurements. The linear regression equation was y = -3.19 + 0.70*x, with a p-value <0.001. The slope and intercept were 0.70 and -3.19, respectively. The relationship explains ~90% (r^2 = 0.90) of the variance that exists between the measurements.

The winter indoor PM_4 mass concentrations from the DT, DTII and SP instruments did not agree as well as the summer measurements *(Figure 3.9.b)*. There is a very good positive correlation (r = 1.0) between the DT and DTII 5-min averaged measurements. The linear regression equation was y = 12.94 + 0.39*x, with a p-value <0.0001. The linear regression had a slope of 0.39 and an intercept of 12.94. Approximately 99% (r^2 = 0.99) of the variation is explained by this relationship. This relationship is also the best compared to those discussed next. There is very good agreement (r = 0.96) between the DT and SP 5-min averaged measurements. The linear regression equation was y = 41.98 + 0.29*x, with a p-value <0.0001. The linear regression had a slope of 0.29 and an intercept of 41.98. Approximately 91% (r^2 = 0.91) of the variation is explained by this relationship. Similar to the DT vs SP, the DTII and SP showed a very good agreement (r = 0.96) between its 5min averages measurements. The linear regression equation was y = 32.94 + 0.77*x, with a p-value <0.001. The slope and intercept were 0.77 and 32.94, respectively. The relationship explains ~92% (r^2 = 0.92) of the variance that exists between the measurements.

There are significant differences in the PM_4 mass concentrations measured by the various photometric instrument models. These differences can be linked back to the level of overestimation by the continuous measurements discussed in *Section 3.1.2 (see Table 3.1)*. The question now remains, does the application of instrument-specific- or mean PCFs improve the comparability of the PM_4 measurements obtained from the DT, DTII, and SP photometric instruments? This is further investigated through a case study.

3.2.3.1. Case study of H024 during winter: comparison of PM_4 with applied PCFs

The application of the photometric calibration factors (PCFs) was evaluated through a case study. Measurements were recorded in H024 situated in KwaZamokuhle, during winter (6 to 22 July 2015). The 5-min averaged data were corrected with PCFs calculated from the continuous and gravimetric measurements for the same period, within the same household. The results were presented in *Section 3.1.2 (see Table 3.1)* above.

A comparison was made between the application of i) a mean PCF for all instruments combined (ΔI) and ii) specific PCFs for individual instrument models (ΔII). The individual instrument PCFs applied to the initial DT, DTII, and SP PM_4 mass concentrations were 0.33, 0.70, and 0.85, respectively. The mean PCF for all instrument models was 0.63. The relationship between the DT, DTII, and SP PM_4 mass concentrations for the initial, mean PCF (ΔI), and individual PCFs (ΔII) are presented in *Figure 3.10 a* to *d*.

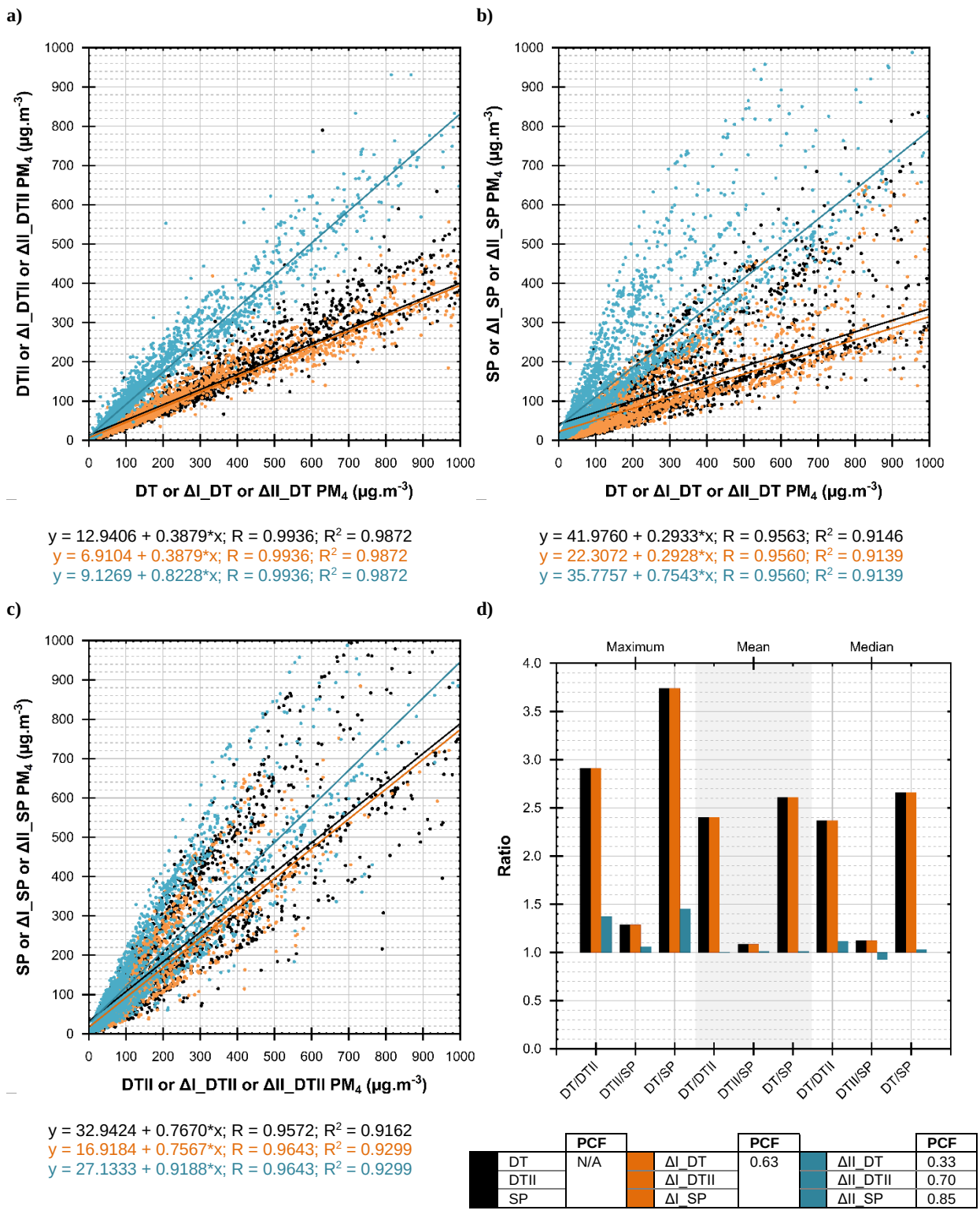


Figure 3.10 Scatterplot of initial (black), corrected by mean PCF_ΔI (orange), and corrected by specific instrument PCFs_ΔII (blue) 5-min averaged collocated PM_4 concentrations ($\mu g.m^{-3}$) measured by DT, DTII, and SP instruments in H24 in KwaZamokuhle from 6 to 22 July 2015 (winter) with a) DTII vs DT, b) SP vs DT and c) SP vs DTII.

In this case study, the application of a mean PCF (ΔI) of 0.63 did not significantly improve the relationship *(Figure 3.10)* between the PM_4 mass concentrations measured by the DT, DTII, and SP instruments. The main reason behind this is the high variability that exists between the PCFs for the individual instruments. The application of the mean PCF improved the mean ΔI_DT readings, however, it is still ~60% higher than expected. The ΔI_DTII and ΔI_SP measurements were over-corrected resulting in measurements that are ~33 and 38% lower than the expected values.

The most significant improvement in the relationship between the instruments was obtained by applying the instrument-specific PCFs (ΔII). The ΔII_DT and ΔII_DTII *(Figure 3.10.a)* instrument measurements showed a very good positive correlation ($r = 0.99$; $r^2 = 0.99$). The linear regression equation was $y = 9.13 + 0.82*x$, with a slope of 0.82 and an intercept of 9.13. This relationship showed ~43% improvement in the comparability of its measurements. The ΔII_DT and ΔII_SP *(Figure 3.10.b)* instrument measurements showed a very good positive correlation ($r = 0.96$; $r^2 = 0.92$). The linear regression equation was $y = 35.78 + 0.75*x$, with a slope of 0.75 and an intercept of 35.78. This relationship showed ~46% improvement in the comparability of its measurements. The ΔII_DTII and ΔII_SP *(Figure 3.10.c)* instrument measurements also showed a very good positive correlation ($r = 0.96$; $r^2 = 0.93$). The linear regression equation was $y = 27.13 + 0.92*x$, with the highest a slope of 0.92 and an intercept of 27.13. This relationship showed ~15% improvement in the comparability of its measurements when compared to the initial concentrations.

There are clear improvements in the relationship between the instruments when considering the instrument ratios for the maximum, mean, and median PM_4 mass concentration measurements *(Figure 3.10.d)*. The ratios of the maximum PM_4 concentrations for the DT/DTII, DTII/SP, and DT/SP have dropped from 2.9, 1.3, and 3.7 to 1.4, 1.1, and 1.4, respectively. This shows a significant reduction in the difference between the maximums measured with the individual instrument models. The ratios of the mean PM_4 mass concentrations were also reduced and are now very close to unity. Similarly there was a significant improvement in ratios of the median PM_4 concentrations. However there is a single instance (DTII/SP) where the ratio was over-reduced from ~1.1 to 0.9. This shows that the PM_4 concentration might be a bit lower than what is expected.

The application of mean PCFs to initial PM_4 measurements should be considered carefully as is could contribute to the over-or under correction of measurements. Based on the above it is better to apply PCFs that were calculated for specific instruments within a specific micro-environment, however, if there is a low variability between the individual PCFs it is possible to use a mean PCF without over-correcting the PM_4 mass concentrations. The PM_4 mass concentrations from the different photometric instrument models are comparable if, and only if, the appropriate PCF is used to correct for any possible over- or underestimations. It is likely that other drivers of the correction factor can be identified and applied in future to improve the quality control procedure.

3.3. Evaluation Study III: Size fraction comparison

The rationale behind this evaluation is to better understand the particle size fractioning within the indoor residential setting. This knowledge can then be used to facilitate the conversion of existing indoor PM_4 data for South Africa into other factions which are more comparable with international studies, as well as air quality guidelines and legislation. This evaluation was based on collocated PM_{10}, PM_4, $PM_{2.5}$, and PM_1 measurements (not corrected by specific PCFs) collected in household H035 in Giyani (Lowveld region), during spring 2016 (sampling campaign 19, *see Table 2.2*). The household is classified as an OSFB house which uses wood on a daily basis for cooking in an outside fireplace. A full description of the house is given in *Section 2.3.2.3.3*.

3.3.1. Temporal trends in PM_{10}, PM_4, $PM_{2.5}$ and PM_1 mass concentrations

The temporal trend of the 5-min averaged values of PM_{10}, PM_4, $PM_{2.5}$, and PM_1 concentrations are given in *Figure 3.11*. The sources impacting this house will influence the relationship between the different size fractions. Higher concentrations of the smaller size fractions ($PM_{2.5}$ and PM_1) are related to combustion activities within the ambient environment *(see A on Figure 3.11)*, while increased concentrations of larger size fraction (PM_{10} and PM_4) are associated with sources such as resuspended dust *(see B on Figure 3.11)* in both the indoor and ambient environment.

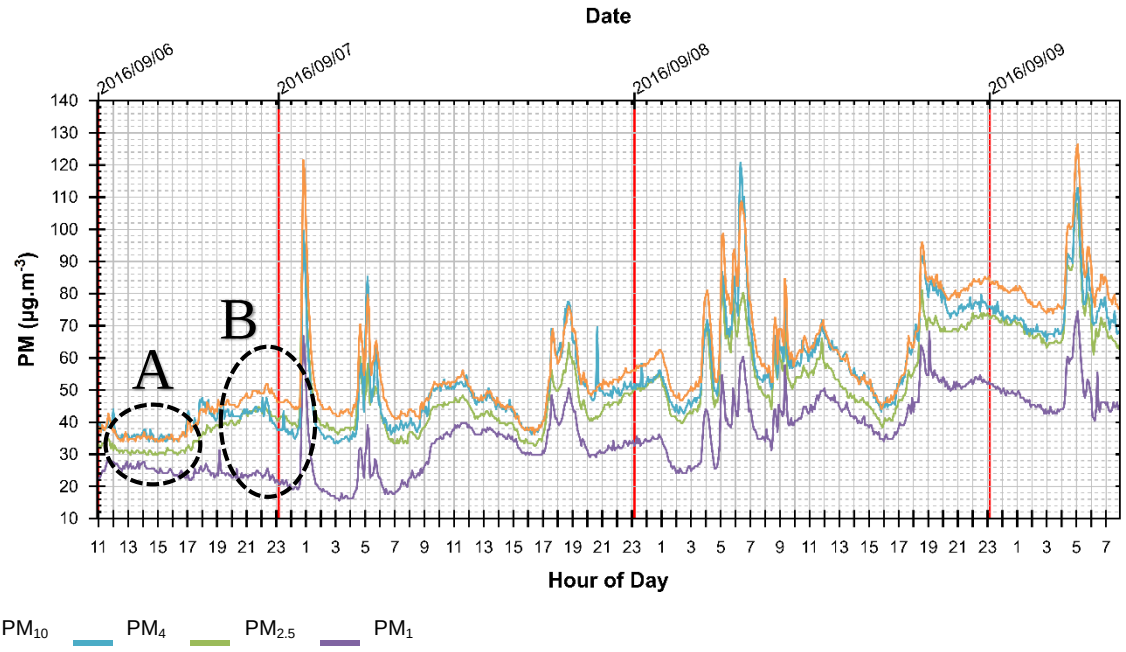


Figure 3.11 Time series of 5-min averaged collocated PM_{10}, PM_4, $PM_{2.5}$, and PM_1 concentration ($\mu g.m^{-3}$) measurements by SidePak AM510 at H035 in Giyani from 6 to 9 September 2016.

The peaks observed throughout the measurement period *(Figure 3.11)* are consistent for all the size fractions, however, there were two instances in which peaks were recorded for individual size fractions that

were not present in the other fractions. The first was for PM_1 on 6 September at approximately 19h00 and the second for PM_4 on 7 September between 20h00 and 21h00. These two peaks could be related to instrument artefacts. Overall there is a clear pattern of association in the recorded measurements of different size fractions.

3.3.2. PM_{10}, PM_4, $PM_{2.5}$ and PM_1 mass concentrations

The concentrations of PM_{10}, PM_4, $PM_{2.5}$, and PM_1 were measured for a period of four (4) days from 6 September (11h50) to 9 September (08h45), 2016. These measurements produced a total of eight-hundred-and-twenty-eight (828) 5-minute averaged data points for each particulate size fraction of which 100% were valid observations. The central tendency and cumulative frequency distribution of the 5-minute averaged data for the PM_{10}, PM_4, $PM_{2.5}$, and PM_1 size fractions are given in *Figure 3.12.a* and *b*.

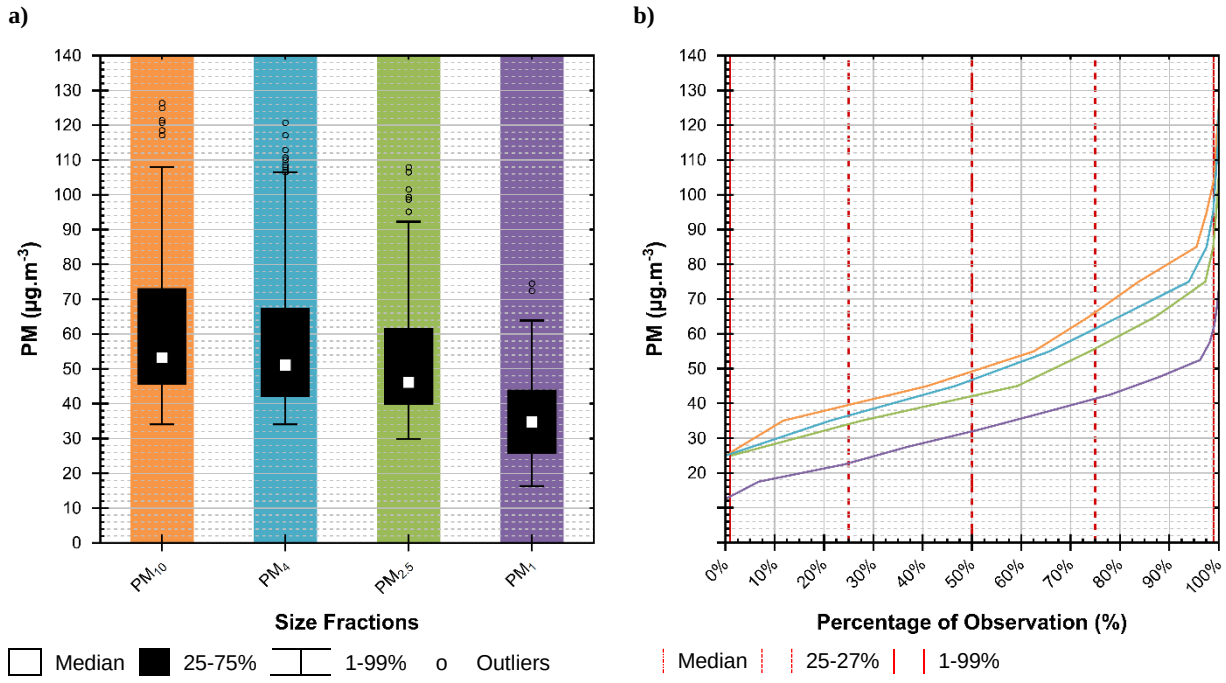


Figure 3.12 a) Box plots showing the central tendency of the data and b) the percentage cumulative frequency distribution for 5-min averaged collocated indoor PM_{10}, PM_4, $PM_{2.5}$, and PM_1 concentration ($\mu g.m^{-3}$) measurements by SidePak AM510 at H035 in Giyani from 6 to 9 September 2016.

The mean (median) ±SD (IQR) [minimum-maximum] indoor particulate concentrations were in the following order: $PM_{10} > PM_4 > PM_{2.5} > PM_1$ *(Figure 3.12.a)*. The PM_{10} size fraction was the highest at 58.6 (53.3) ±17.6 (27.7) [34.1-126.0]. The mean PM_{10} was a factor of 1.07 and 1.17 higher than the PM_4 (54.7 (51.1) ±16.0 (25.6) [33.4-121.0]) and $PM_{2.5}$ (50.3 (46.2) ±14.7 (22.0) [29.8-108.0]) mass concentrations. The largest difference was between the PM_{10} and PM_1 mass concentrations. The mean PM_{10} was a factor of 1.65 higher than the PM_1 (35.6 (34.8) ±11.4 (18.4) [15.6-74.6]). The cumulative frequency distribution

(Figure 3.12.b) indicated that the majority of observations ranged between approximately 30 and 70 µg.m^{-3}, for PM_{10}, PM_4, and $PM_{2.5}$, respectively. However, for PM_1 it ranged between about 20 and 45 µg.m^{-3}.

3.3.3. Comparison between PM_{10}, PM_4, $PM_{2.5}$ and PM_1 mass concentrations

Ratios were used as an indicator for evaluating the difference in indoor mass concentrations measured between the various size fractions (PM_{10}, PM_4, $PM_{2.5}$, and PM_1). Ratios closer to one (1) indicate smaller variation in mass concentrations between the size fractions being compared. Ratios further from one (1) signify larger differences in the mass concentrations between the size fractions. The ratios of PM_4/PM_{10}, $PM_{2.5}/PM_{10}$, PM_1/PM_{10}, $PM_{2.5}/PM_4$, PM_1/PM_4, and $PM_1/PM_{2.5}$ for the indoor environment are summarised in *Figure 3.13*. The mean (median) ±SD (IQR) [minimum-maximum] ratios are as follow:

- PM_4 / PM_{10} : 0.94 (0.94) ±0.07 (0.09) [0.76-1.36]
- $PM_{2.5}$ / PM_{10} : 0.86 (0.87) ±0.04 (0.04) [0.70-1.17]
- PM_1 / PM_{10} : 0.61 (0.61) ±0.11 (0.16) [0.37-0.84]
- $PM_{2.5}$ / PM_4 : 0.92 (0.92) ±0.08 (0.08) [0.59-1.28]
- PM_1 / PM_4 : 0.65 (0.66) ±0.09 (0.13) [0.41-0.83]
- PM_1 / $PM_{2.5}$: 0.71 (0.71) ±0.12 (0.18) [0.42-0.94]

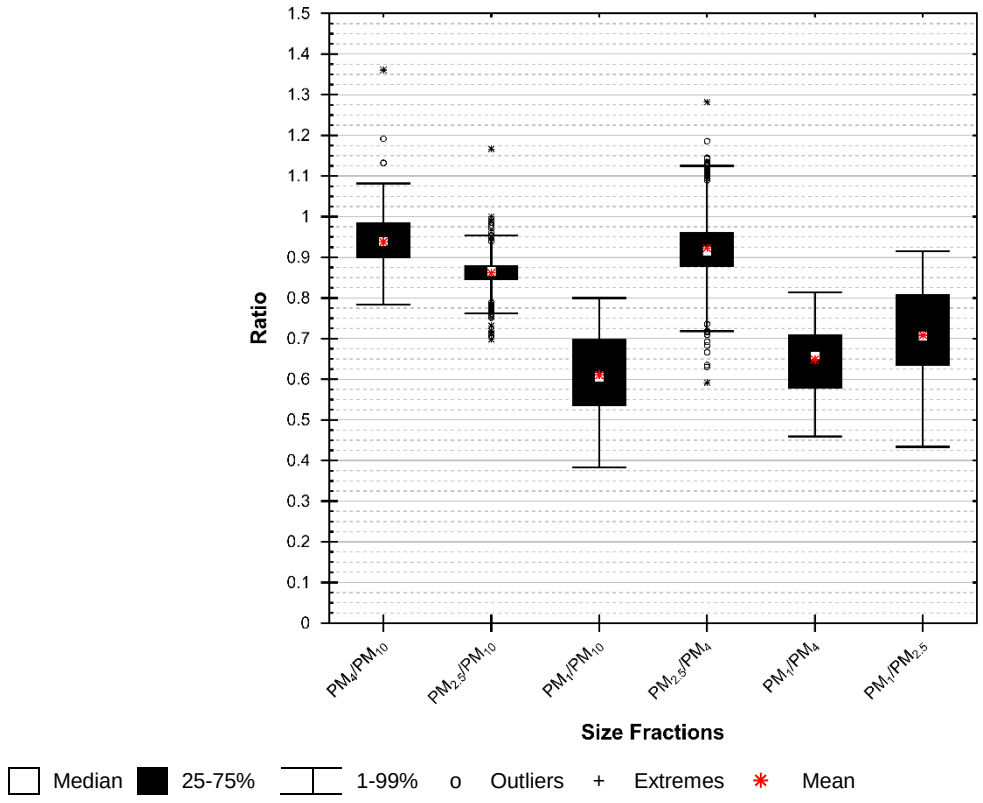


Figure 3.13 Box plots showing the mean ratios of the PM_{10}, $PM_{2.5}$, PM_4, and PM_1 size fraction for the residential indoor environment.

It is clear that the PM_{10}, PM_4 and $PM_{2.5}$ measurements are closely related to one another, whereas PM_1 concentration tendency and frequency distribution differ a lot more compared to the other size fractions. The most important ratio for this study is that of $PM_{2.5}/PM_4$ (0.92). It is required to convert the existing PM_4 measurement to $PM_{2.5}$ so as to facilitate the comparison with the $PM_{2.5}$ NAAAQS and WHO guidelines.

The conversion of mass concentrations from one size fraction to another is based on *Equation 3.1*, below:

$$\Delta PM_x = PM_y \times Rt_{x:y}$$

Equation 3.1. Conversion of PM mass concentrations between size fractions ($\mu g.m^{-3}$).

, where ΔPM_x is the converted mass concentrations for size fraction x in $\mu g.m^{-3}$, PM_y is the initial recorded mass concentration of size fraction y in $\mu g.m^{-3}$, and $Rt_{x:y}$ is the mean ratio given calculated above.

The $PM_{2.5}/PM_4$ conversion factor of 0.92 was applied to the data as described above in *Equation 3.1*. Looking specifically at the initial $PM_{2.5}$ (50.3 (46.2) ±14.7 (22.0) [29.8-108.0]) compared to the $\Delta PM_{2.5}$ (50.3 (47.0) ±14.7 (33.6) [30.7-111.0]) it is apparent that the mean ±SD concentration is exactly the same. The $\Delta PM_{2.5}$ median, minimum, and maximum concentrations are higher by 0.8 $\mu g.m^{-3}$ (1.73%), 0.9 $\mu g.m^{-3}$ (3.02%), and 3.0 $\mu g.m^{-3}$ (2.78%), respectively. The conversion of respirable- to the fine particle fraction is thus considered to be accurate when comparing the initial $PM_{2.5}$ to the $\Delta PM_{2.5}$.

3.3.3.1. Contribution of PM_{10}, PM_4, $PM_{2.5}$ and PM_1

Based on the ratios discussed in the previous section. The percentage contribution of PM_4, $PM_{2.5}$, and PM_1 to PM_{10} were calculated to be ~93, ~86, and ~61%, respectively *(Figure 3.14)*. Considering only the PM_4 fraction, the contribution of $PM_{2.5}$ is ~92%, while PM_1 makes up ~65% of total respirable fraction. Taking into account only the $PM_{2.5}$, the ultrafine PM_1 fraction contributes ~70% to the total fine fraction.

This collocated size fraction comparison study shows that the majority of the suspended particles sampled within the residential indoor environment is of the respirable size fraction and smaller. This is significant as smaller particles are associated with human increased health *(see Chapter 1, Section 1.2.3.1)*. It also supports the idea of converting the existing respirable (PM_4) mass concentration measurement to $PM_{2.5}$ in order to facilitate comparisons with NAAQS and WHO guidelines. This will improve the comparability of the findings within this study to that of international studies.

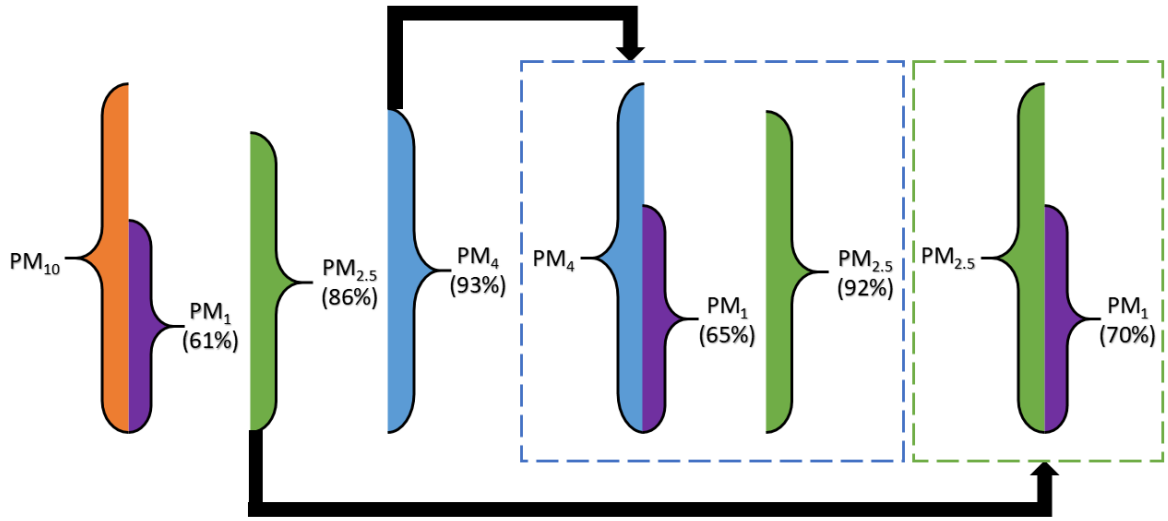


Figure 3.14 Summary of the reconstructed mean percentage contribution of PM_4, $PM_{2.5}$, and PM_1 size fractions to PM_{10}, PM_4, and PM_1.

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This chapter addressed the results and discussions surrounding Objective I, as outlined in *Chapter 1, Section 1.4*, which focused on the field evaluation of the continuous photometric instruments used in this study. The three areas of concern related to the accuracy, comparability, and size-fractionation were investigated. It was found that the instruments both over- and underestimated the respirable particulate mass concentrations, however, on average it was overestimated by a factor of almost two. Individual PCFs have been calculated for the specific micro-environments within the coal burning-, urban-, and wood-burning communities. These PCFs have been applied to the data discussed in *Chapter 4*. The measurements obtained from the DT, DTII, and SP photometric instruments were found to be comparable when corrected by an appropriate PCF. Conversion factors have been calculated to accurately convert between different size fractions for the purpose of comparing existing measurements to air quality guidelines and standards. The contribution of the PM_{10}, PM_4, $PM_{2.5}$, and PM_1 size fractions have also been determined. The following chapter addresses the characterisation of indoor PM_4 across the various communities.

CHAPTER 4: CHARACTERISATION AND SOURCE IDENTIFICATION OF RESPIRABLE INDOOR PARTICULATE MATTER

This chapter aims to address the results and discussion surrounding Objective II and III, as outlined in *Chapter 1 Section 1.4*. The characterisation is done based on the levels of respirable particulate matter, both continuous *(see Chapter 2, Section 2.3.2.1)* and gravimetric *(see Chapter 2, Section 0)*, as well as the observed elemental mass concentrations. The possible sources are apportioned based on the elements present in the indoor environment. The spatial and temporal variability of the above is compared across the various low-income residential communities within the Highveld and Lowveld regions of South Africa. The differences are outlined and explored in more detail.

****

4.1. Spatial and temporal variability of indoor PM_4 mass concentrations

4.1.1. Continuous indoor PM_4 mass concentrations

The mean (median) ±SD (IQR) [minimum-maximum] residential indoor PM_4 mass concentrations for the five low-income settlements sampled in this study was 116 (37) ±357 (61) [1-9913] $\mu g.m^{-3}$. The continuous indoor PM_4 concentrations within the three communities were in the flowing order: coal > wood > urban. The coal-burning communities had the highest mean indoor PM_4 at 137 (39) ±403 (72) [1-9913] $\mu g.m^{-3}$. This was a factor of 2.59 and 2.53 higher than the urban- (53 (20) ±171 (33) [1-9408] $\mu g.m^{-3}$) and outside wood-burning (58 (31) ±143 (41) [1-4979] $\mu g.m^{-3}$) communities, respectively.

This indicated that the people residing within coal-burning communities are continuously exposed to indoor loading of respirable particulate matter which are up to three times that on non-coal-burning communities. These populations could therefore experience higher levels of negative health impacts, such as respiratory infections, associated with increased particulate loadings.

Settlement variations of continuous PM_4 mass concentrations

The individual settlements had varying levels of particulate pollution. The continuous indoor PM_4 concentrations within the five settlements were in the following order: KwaDela > KwaZamokuhle > Giyani > Jouberton > Agincourt. The coal-burning settlement of KwaDela (154 (36) ±480 (62) [1-9368] $\mu g.m^{-3}$) had the highest mean indoor PM_4. It was a factor of 1.34 higher than the second coal-burning settlement of KwaZamokuhle (115 (44) ±268 (84) [1-9913] $\mu g.m^{-3}$). The urban settlement of Jouberton (53 (20) ±171 (33) [1-9408] $\mu g.m^{-3}$) was a factor of 0.38 lower than KwaDela. The wood-burning settlements of Agincourt (51 (29) ±119 (34) [2-4863] $\mu g.m^{-3}$) and Giyani (84 (38) ±212 (73) [1-4979] $\mu g.m^{-3}$) were a factor of 0.33 and 0.55 lower than KwaDela.

The above indicates that a high variability, in continuous PM_4 loadings, exists between settlements that have the same fuel use classification. KwaDela and KwaZamokuhle are expected to have similar ambient particulate levels as a result of similar regional sources impacting on their geographic locations, which are a mere 70km apart. However, from the above results KwaDela experiences ~30% higher indoor PM_4 compared to KwaZamokuhle. This difference could be attributed to the level of indoor solid fuel combustion activities occurring within the households. Thus, the assumption is made that residents within KwaDela might be burning more consistently throughout the year compared to KwaZamokuhle. A similar observation is made for the wood-burning settlements of Agincourt and Giyani. These observation and assumptions are supported by the energy fuel use results obtained through the national census and household surveys discussed in *Chapter 2, Section* ***Error! Reference source not found.*** *(see Figure 2.19.a-).*

Seasonal variations of continuous PM_4 mass concentrations

The mean seasonally categorised spread of the continuously measured residential indoor PM_4 was in the following order: spring (128 (64) ±326 (109) [1-9913] $\mu g.m^{-3}$) > summer (115 (33) ±438 (43) [1-9368] $\mu g.m^{-3}$) > winter (111 (64) ±257 (70) [1-9209] $\mu g.m^{-3}$). However, when it is categorised by both settlement and season, there is a definite distinction in indoor PM_4 that starts to appear.

The spring concentrations of continuous indoor PM_4 within the settlements were in the following order: KwaZamokuhle > Giyani. The mean indoor PM_4 in KwaZamokuhle was 130 (57) ±349 (111) [1-9913] $\mu g.m^{-3}$, followed closely by the outside wood-burning community of Giyani (115 (93) ±105 (82) [9-2377] $\mu g.m^{-3}$). These springtime measurements were higher than those experienced during summer (both in KwaZamokuhle and Giyani) and winter in Giyani.

The summer concentrations of continuous indoor PM_4 within the settlements were in the following order: KwaDela > Giyani > KwaZamokuhle > Agincourt > Jouberton. KwaDela experienced extremely high indoor PM_4 loadings during summer at 180 (33) ±622 (49) [1-9368] $\mu g.m^{-3}$. The mean indoor PM_4 loadings in KwaDela were a factor of 2.93, 3.65, and 3.35 higher than KwaZamokuhle (61 (33) ±111 (46) [1-3001]

µg.m^{-3}), Jouberton (49 (20) ±205 (30) [1-9408] µg.m^{-3}), and Agincourt (54 (30) ±148 (33) [2-4853] µg.m^{-3}). The summer means indoor PM_4 in Giyani (108 (62) ±166 (70) [5-3752] µg.m^{-3}) was the closest to that of KwaDela (a factor of 1.67 higher).

The winter concentrations of continuous indoor PM_4 within the settlements were in the following order: KwaZamokuhle > KwaDela > Jouberton > Giyani > Agincourt. KwaZamokuhle had the highest indoor PM4 levels during the winter at 161 (55) ±302 (132) [3-8890] µg.m^{-3}. It was a factor of 1.23 higher than its fellow coal-burning settlements KwaDela (131 (39) ±302 (79) [1-9209] µg.m^{-3}). The remaining three settlements of Jouberton (57 (21) ±129 (36) [1-4243] µg.m^{-3}), Agincourt (48 (28) ±78 (35) [2-4498] µg.m^{-3}), and Giyani (50 (12) ±269 (13) [1-4979] µg.m^{-3}) had similar mean indoor PM_4 loading. The indoor PM_4 levels in these settlements were factors of 0.35, 0.30, and 0.31 lower than KwaZamokuhle.

The above results indicate a more complex relationship between the mean indoor PM_4 loadings and seasonality within the various settlements. Only two settlements conform to the expected seasonal ranking of winter > spring > summer, namely KwaZamokuhle and Jouberton. In KwaDela and Agincourt the summer loading were higher than the winter loadings by factors of 1.11 and 1.13, indicating a ~10 to 15% higher indoor PM_4 loading during summer. Giyani had a unique seasonal ranking of spring > summer > winter, whereby the spring loadings were 1.06 and 2.3 times higher than summer and winter, respectively. This is the inverse of the expected, indicating the presence of specific particulate generating sources during spring and summer in and around Giyani. These sources could possibly include regional biomass burning and enhanced levels of windblown dust due to the lack of vegetation cover.

Household variations of continuous PM_4 mass concentrations

Based on the household fuel use classification, the mean continuous indoor PM_4 was in the following order: indoor solid fuel burning (ISFB) > non-solid fuel burning (NSFB) > outdoor solid fuel burning (OSFB). The ISFB dwellings had a mean indoor PM_4 loading of 141 (38) ±425 (69) [1-9913] µg.m^{-3}. This was a factor of 2.39 and 2.48 higher than the NSFB (59 (28) ±149 (42) [1-9408] µg.m^{-3}) and OSFB (57 (28) ±153 (36) [1-4979] µg.m^{-3}) households. The variability in the indoor PM_4 for individual households, categorised by fuel use and season, is presented in *Figure 4.1.a* to *c*.

The mean continuous PM_4 during spring *(Figure 4.1.a)* was in the following order: ISFB > OSFB > NSFB. In KwaZamokuhle (coal-burning) the ISFB houses had mean indoor PM_4 concentrations of 152 (46) ±420 (99) [10-1-9913] µg.m^{-3}. While in Giyani (wood-burning), the OSFB > NSFB. The OSFB houses had the highest level of indoor PM_4 at 138 (109) ±133 (91) [10-1760] µg.m^{-3}. It was a factor of 1.57 higher than the NSFB (87 (71) ±124 (64) [9-4585] µg.m^{-3}) households. Thus, the ISFB was higher b factors of 1.10 and 1.75 higher than the OSFB and NSFB dwellings.

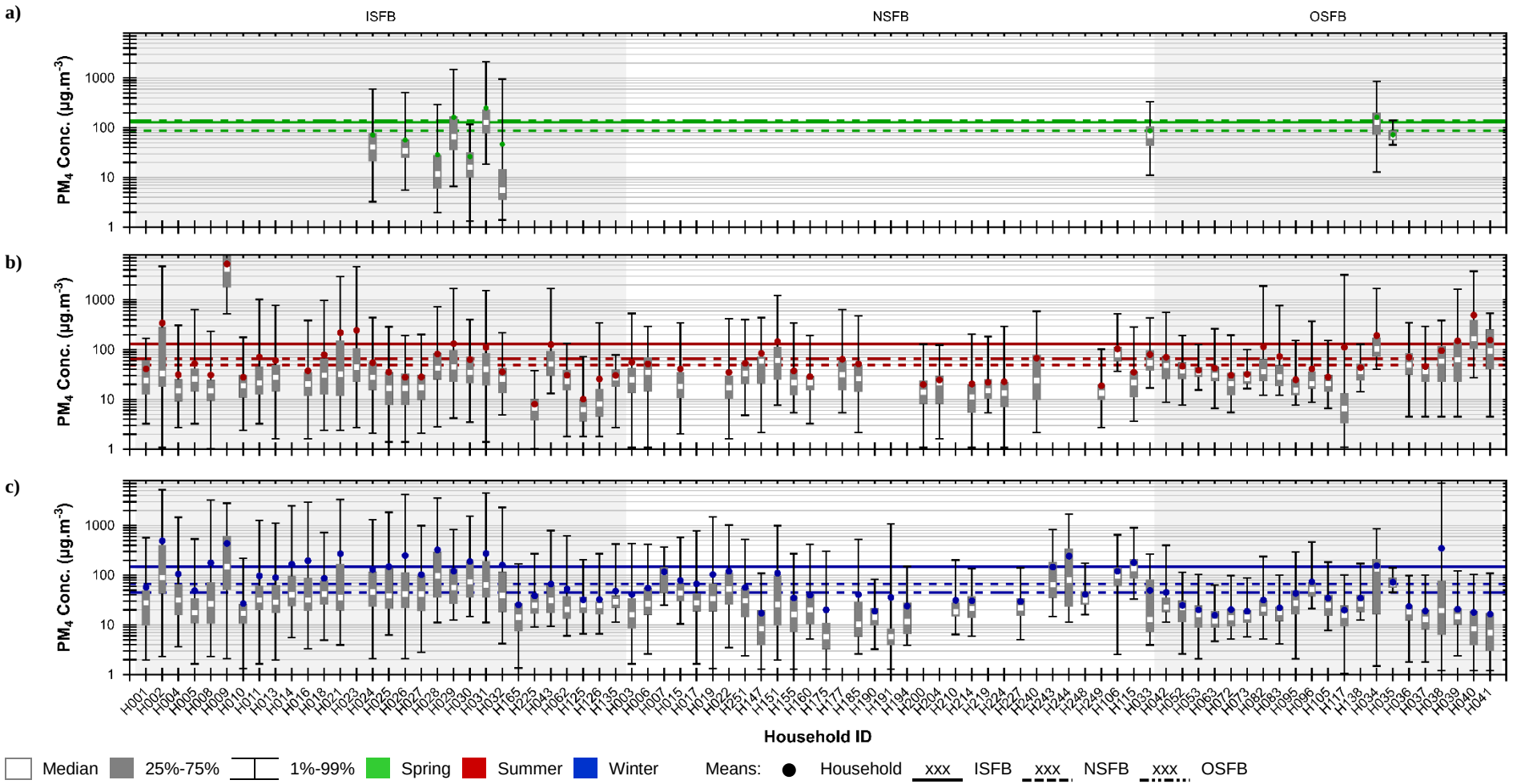

Figure 4.1 Box plots of the 5-min averaged continuous indoor PM_4, showing the household variability of particles measured in the ISFB, NSFB, and OSFB households within KwaDela, KwaZamokuhle, Jouberton, Agincourt, and Giyani (2013-2017) during a) spring, b) summer, and c) winter.

The summer and winter showed similar trends to the overall mean indoor PM_4 mass concentrations of the ISFB, NSFB, and OSFB dwelling. During summer, the mean continuous PM_4 during spring was in the following order: ISFB > OSFB > NSFB. The ISFB households had the highest indoor PM_4 loading during the summer *(Figure 4.1.b)* at 130 (31) ±483 (49) [1-9368] $\mu g.m^{-3}$. This was a factor of 2.66 and 1.96 higher than the NSFB (49 (25) ±154 (34) [1-9408] $\mu g.m^{-3}$) and OSFB (66 (36) ±148 (38) [1-4853] $\mu g.m^{-3}$) houses. The settlements of KwaDela, KwaZamokuhle and Jouberton followed the expected as the ISFB households had higher mean loadings the NSFB dwellings during summer. However, the wood burning-settlements of Agincourt and Giyani varied as the OSFB > NSFB > ISFB.

During winter *(Figure 4.1.c)*, the mean continuous PM_4 during spring was in the following order: ISFB > NSFB > OSFB. The ISFB dwellings had the highest mean indoor PM_4 at 148 (41) ±371 (82) [1-9240] $\mu g.m^{-3}$. The ISFB houses were a factor of 2.22 and 3.30 higher than the NSFB (67 (31) ±138 (50) [1-4349] $\mu g.m^{-3}$) and OSFB (45 (20) ±158 (23) [1-4979] $\mu g.m^{-3}$) households. Similarly to summer, the ISFB particulate loadings were higher than the NSFB in KwaDela, KwaZamokuhle, and Jouberton. Yet again, Agincourt (NSFB > ISFB > OSFB) and Giyani (OSFB > ISFB > NSFB) are different.

This indicates that for both the coal-burning settlements (KwaDela and KwaZamokuhle) as well as the urban settlement (Jouberton), the highest level of exposure occurs within the ISFB households during all seasons. However, this is not the case within the more rural wood-burning settlements (Agincourt and Giyani). The variations within these settlements could possibly be influenced by solid fuel burning practices (in rural areas burning is frequently conducted outdoors in a designated cooking area) as well as the proximity dwellings to one another. The potential for infiltration to take place through open doors and windows is higher in urban townships.

The particulate loadings are not constant throughout the day and night as it can be influenced by both indoor and ambient sources. The diurnal variations of the residential indoor PM_4 mass concentrations is explored in the following section.

4.1.1.1. Diurnal patterns of indoor PM_4 mass concentrations

The hourly averaged residential indoor PM_4 mass concentrations were calculated from the 5-min averaged measurements. Hourly means with less than 50% valid observations were excluded from further analysis. The diurnal variation in the indoor PM_4 loadings for the ISFB, NSFB, and OSFB households, categorised by community and season, are shown in *Figure 4.2* to *Figure 4.4*.

4.1.1.1.1. Diurnal pattern within the coal-burning communities

The season diurnal variations for the coal-burning communities are shown in *Figure 4.2*. During the spring *(Figure 4.2.a)*, in the ISFB dwellings, the PM_4 loadings increased between 03h00 and 10h00 (peaking

around 06h00 at 277 (150) ±58 (361) [8-1189] µg.m^{-3}) and between 15h00 and 20h00 (peaking around 17h00 at 233 (135) ±264 (147) [28-1127] µg.m^{-3}). Thus, there was an increased particulate loading for a period of seven (7) hours during the morning and five (5) hours in the evening.

During the summer *(Figure 4.2.b)*, in the ISFB households, the indoor PM_4 levels are elevated between 05h00 to 11h00 (peaking around 08h00 at 176 (61) ±416 (94) [5-4293] µg.m^{-3}) and in the evening between 16h00 and 20h00 (peaking around 19h00 at 307 (86) ±791 (114) [13-5159] µg.m^{-3}). Thus, the hours of elevated particulate matter was slightly less during the summer (compared to spring) with a period of six (6) hours during the morning and four (4) hours in the evening. The mean summer morning peak was a factor of 0.64 lower than the spring, while the evening peak was 1.32 times higher. In NSFB dwellings the indoor PM_4 loadings were elevated in the morning between 06h00 to 11h00 (peaking around 10h00 at 58 (31) ±101 (41) [2-660] µg.m^{-3}) and in the evening between 17h00 and 20h00 (peaking around 19h00 at 94 (45) ±160 (89) [7-1268] µg.m^{-3}). The NSFB houses experienced reduced periods of elevated particulate loadings, compared to the ISFB dwelling. The ISFB households mean summer morning- and evening peaks were factors of 3.04 and 3.27 times higher than those of the NSFB.

During the winter *(Figure 4.2.c)*, in the ISFB households, the indoor PM_4 levels are elevated between 04h00 to 09h00 (peaking around 07h00 at 321 (173) ±361 (423) [4-2013] µg.m^{-3}) and in the evening between 15h00 and 22h00 (peaking around 18h00 at 518 (349) ±586 (564) [6-3831] µg.m^{-3}). Thus, the hours of elevated particulate matter was similar to spring with a period of five (5) hours during the morning and seven (7) hours in the evening. The mean winter morning- and evening peaks were factors of 1.82 and 1.68 times higher than during the summer. In NSFB dwellings the indoor PM_4 loadings were elevated in the morning between 05h00 to 10h00 (peaking around 07h00 at 91 (47) ±101 (82) [5-686] µg.m^{-3}) and in the evening between 16h00 and 21h00 (peaking around 18h00 at 231 (148) ±230 (272) [20-1454] µg.m^{-3}). Similar to the summer, the NSFB dwellings had reduced periods of increased particulate loadings compared to the ISFB.

The mean winter morning- and evening peaks, in the NSFB, were 1.56 and 2.46 times higher than during the summer in coal-burning communities. The ISFB mean winter morning- and evening peaks were factors of 3.54 and 2.24 times higher than those of the NSFB dwellings. Thus, the residents within the ISFB households are exposed to higher levels of particulate pollution for longer periods than the occupant of NSFB dwellings. The extended periods of extreme exposure could lead to increased occurrences of various health impacts.

The distinct bi-modal peak for the indoor PM_4 loadings within the low-income residential communities mirrors the ambient diurnal concentration of particulate matter in these communities (Adesina *et al.*, 2020; Language *et al.*, 2016; Wernecke *et al.*, 2015).

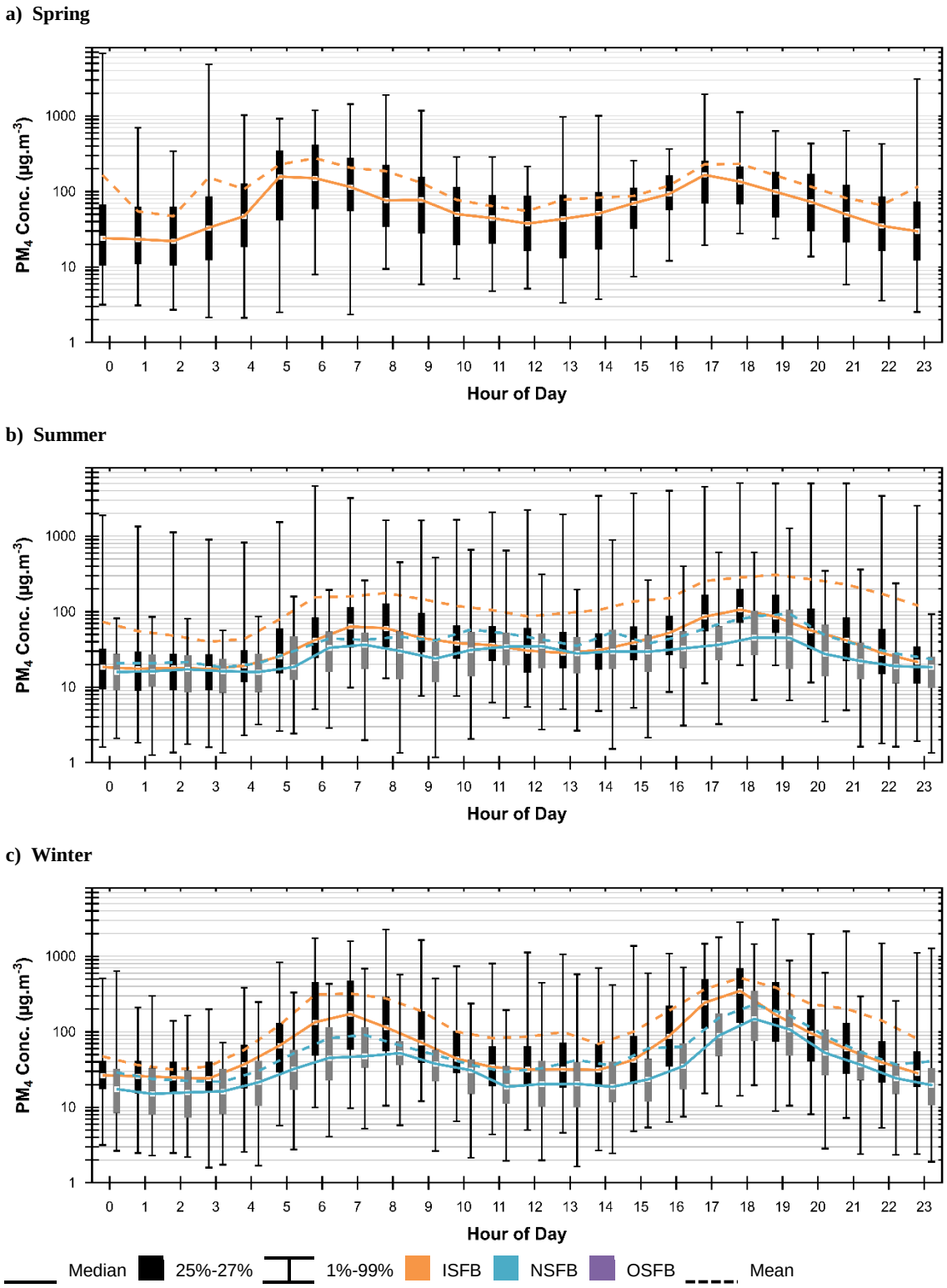

Figure 4.2 Box plots showing the spread and diurnal variation of the hourly averaged residential indoor PM_4, measured in the coal-burning communities of KwaDela and KwaZamokuhle during a) spring, b) summer, and c) winter.

4.1.1.1.2. Diurnal pattern within the urbanised community

The season diurnal variations for the urbanised community are shown in *Figure 4.3*. During the summer *(Figure 4.3.a)*, in the ISFB households, the indoor PM_4 levels are elevated between 05h00 to 09h00 (peaking around 07h00 at 125 (129) ±59 (117) [54-192] µg.m^{-3}) and in the evening between 15h00 and 19h00 (peaking around 17h00 at 158 (187) ±69 (99) [58-216] µg.m^{-3}). Thus, the particulate loadings were elevated for a period of four (4) hours during the morning and evening, respectively. In NSFB dwellings the indoor PM_4 loadings were elevated in the morning between 05h00 to 09h00 (peaking around 06h00 at 90 (33) ±139 (90) [4-795] µg.m^{-3}) and in the evening between 18h00 and 22h00 (peaking around 20h00 at 104 (60) ±109 (114) [5-431] µg.m^{-3}). The ISFB households mean summer morning- and evening peaks were factors of 1.38 and 1.52 times higher than those of the NSFB. The difference between the ISFB and NSFB dwellings in the urban community is smaller than that seen in the coal-burning communities.

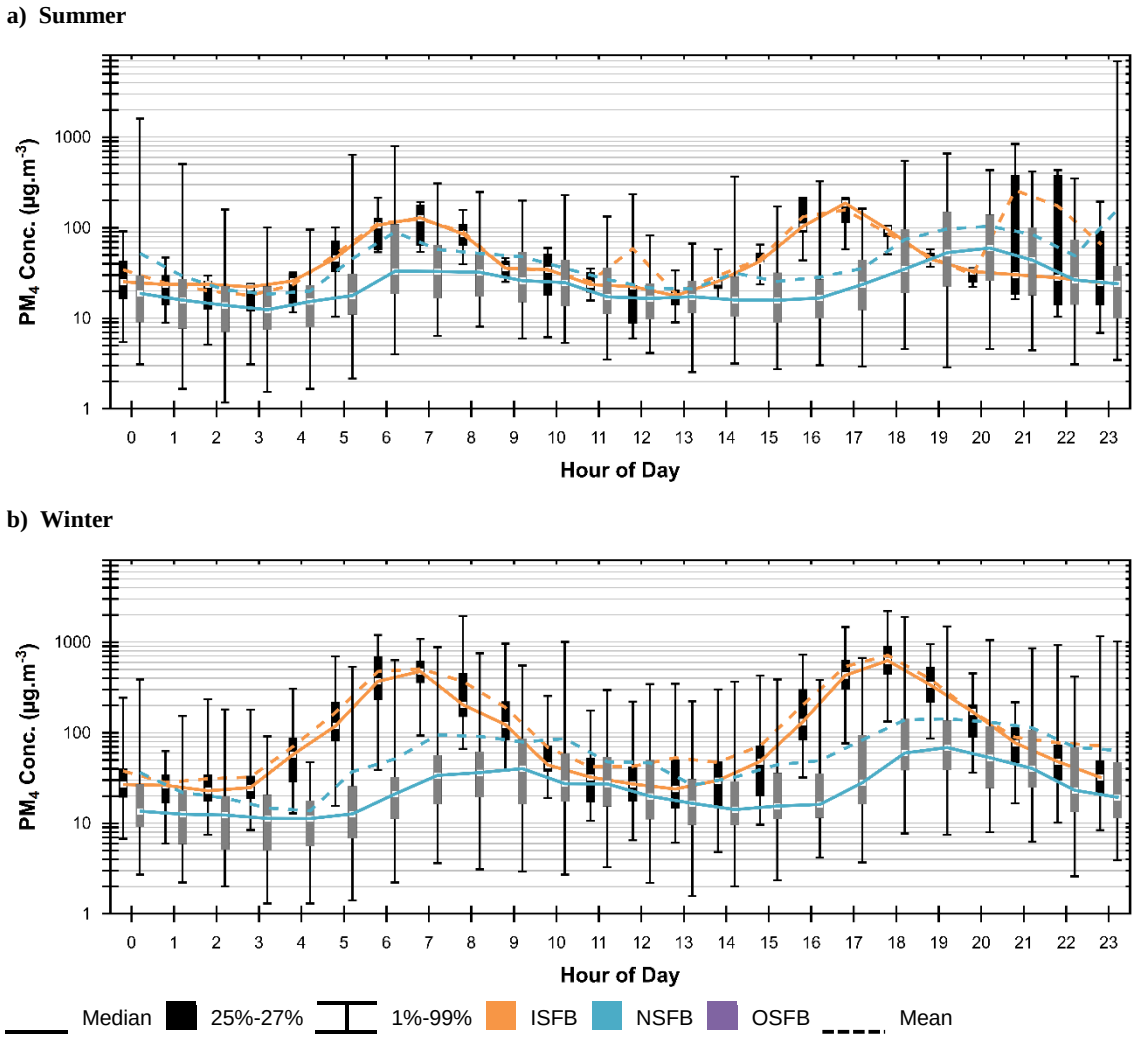

Figure 4.3 Box plots showing the spread and diurnal variation of the hourly averaged residential indoor PM_4, measured in the urban community of Jouberton during a) summer and b) winter.

During the winter *(Figure 4.3.b)*, in the ISFB households, the indoor PM_4 levels are elevated between 04h00 to 10h00 (peaking around 07h00 at 507 (476) ±240 (274) [93-1082] $\mu g.m^{-3}$) and in the evening between 15h00 and 21h00 (peaking around 17h00 at 537 (430) ±368 (334) [77-1471] $\mu g.m^{-3}$). Thus, the hours of elevated particulate matter was more than summer with a period of six (6) hours during the morning and evening, respectively. The mean winter morning- and evening peaks were factors of 4.07 and 3.41 times higher than during the summer. This difference is approximately two (2) times higher than what was experienced in the coal-burning communities. In NSFB dwellings the indoor PM_4 loadings were elevated in the morning between 06h00 to 11h00 (peaking around 07h00 at 95 (34) ±179 (40) [4-883] $\mu g.m^{-3}$) and in the evening between 16h00 and 22h00 (peaking around 19h00 at 143 (68) ±225 (98) [7-1494] $\mu g.m^{-3}$). The mean winter morning- and evening peaks, in the NSFB, were factors of 1.05 and 1.38 times higher than during the summer.

The NSFB dwellings show a smaller seasonal variation in the urban- compared to the coal-burning communities. The ISFB mean winter morning- and evening peaks were factors of 5.35 and 3.76 times higher than those of the NSFB dwellings. The difference between the ISFB and NSFB dwellings is higher in the urban- compared to the coal-burning communities.

4.1.1.1.3. Diurnal pattern within the wood-burning communities

The season diurnal variations for the wood-burning communities are shown in *Figure 4.4*. During the spring *(Figure 4.4.a)*, in the NSFB dwellings, the PM_4 loadings increased between 05h00 and 08h00 (peaking around 06h00 at 244 (178) ±251 (266) [25-823] $\mu g.m^{-3}$) and between 18h00 and 21h00 (peaking around 19h00 at 194 (130) ±201 (97) [48-700] $\mu g.m^{-3}$). Thus, there was an increased particulate loading for a period of three (3) hours during the morning and three (3) hours in the evening. The OSFB dwellings, the PM_4 loadings increased between 05h00 and 09h00 (peaking around 08h00 at 112 (103) ±76 (117) [29-236] $\mu g.m^{-3}$) and between 17h00 and 21h00 (peaking around 18h00 at 287 (261) ±147 (238) [81-504] $\mu g.m^{-3}$). The OSFB households mean summer morning- and evening peaks were factors of 2.18 and 1.48 times higher than those of the NSFB.

During the summer *(Figure 4.4.b)*, in the ISFB households, the indoor PM_4 levels are elevated between 07h00 to 10h00 (peaking around 10h00 at 47 (29) ±46 (39) [2-154] $\mu g.m^{-3}$) and in the evening between 18h00 and 22h00 (peaking around 21h00 at 157 (42) ±484 (43) [3-2536] $\mu g.m^{-3}$). Thus, the particulate loadings were elevated for a period of three (3) hours during the morning and four (4) in the evening. In NSFB dwellings the indoor PM_4 loadings were elevated in the morning between 04h00 to 09h00 (peaking around 07h00 at 112 (90) ±73 (79) [13-272] $\mu g.m^{-3}$) and in the evening between 17h00 and 22h00 (peaking around 19h00 at 131 (124) ±90 (91) [10-391] $\mu g.m^{-3}$). The NSFB households mean spring evening peak were factors of 1.48 times higher than the summer NSFB. The morning peaks were exactly the same. In the OSFB dwellings the indoor PM_4 loadings were elevated in the morning between 06h00 to 10h00

(peaking around 07h00 at 110 (61) ±154 (59) [3-863] µg.m^{-3}) and in the evening between 17h00 and 21h00 (peaking around 20h00 at 144 (50) ±403 (56) [3-3067] µg.m^{-3}). The OSFB dwellings mean spring morning- and evening peaks were factors of 2.22 and 2.00 times higher than during the summer. The morning peak in the ISFB dwellings was a factor of 0.42 lower than those of the NSFB- and OSFB households. The evening peaks were very similar, however, the ISFB houses were slightly higher than the OSFB. With the NSFB dwellings having the lowest evening peak.

During the winter *(Figure 4.4.c)*, in the ISFB households, the indoor PM_4 levels are elevated between 07h00 to 09h00 (peaking around 08h00 at 68 (46) ±61 (40) [19-312] µg.m^{-3}) and in the evening between 17h00 and 20h00 (peaking around 18h00 at 138 (61) ±248 (61) [20-1088] µg.m^{-3}). The ISFB dwellings mean winter morning- and evening peaks were factors of 1.45 higher and 0.88 times lower than during the summer. In NSFB dwellings the indoor PM_4 loadings were elevated in the morning between 05h00 to 10h00 (peaking around 08h00 at 189 (95) ±218 (235) [7-696] µg.m^{-3}) and in the evening between 16h00 and 21h00 (peaking around 209h00 at 156 (156) ±192 (302) [11-598] µg.m^{-3}). The NSFB households mean winter morning- and evening peaks were factors of 1.69 and 1.59 times higher than the summer. In the OSFB dwellings the indoor PM_4 loadings were elevated in the morning between 06h00 to 09h00 (peaking around 07h00 at 56 (29) ±68 (44) [8-439] µg.m^{-3}) and in the evening between 17h00 and 21h00 (peaking around 18h00 at 81 (41) ±246 (42) [2-2194] µg.m^{-3}). The OSFB dwellings mean winter morning- and evening peaks were factors of 0.51 and 0.56 times lower than during the summer.

The observations made in the wood-burning communities varies from that observed in other countries. In Dhaka, Bangladesh *(Salje et al., 2014)* the households and communities typically had a trimodal pattern with peaks occurring in the morning (08:30), early afternoon (13:45) and evening (20:00). The $PM_{2.5}$ concentrations during these peak periods often exceeded 1000 µg.m^{-3}.

There is a distinct bi-modal peak for the indoor PM_4 loadings within the different low-income residential communities, in South Africa. The intensity and duration of the morning- and evening peaks experience a definite seasonal variability. The winter peaks are much higher than those recorded during the summer. This means that the residents are exposed to higher particulate concentrations, for a longer period of time, during the winter. The impact of this is further increased by reduced ventilation and longer time spent indoor during winter. Furthermore, the persons residing in ISFB households are at higher risk of experiencing issues related to health as these household typically have particulate loading three to five times higher than the NSFB and OSFB houses. However, due to the urbanised- and wood-burning communities showing increased variations between the ISFB-, NSFB-, and OSFB dwellings compared to the coal-burning communities, the following deductions are postulated : i) that a higher ambient loading of particulate matter within the community results in a reduced difference between the indoor PM_4 loadings measured within the ISFB- and NSFB households; and ii) proportionally in the urban communities where

solid fuel burning is not prevalent, the impact of burning activities within specific households could proportionally have a significant impact on those residents compared to the coal-burning communities.

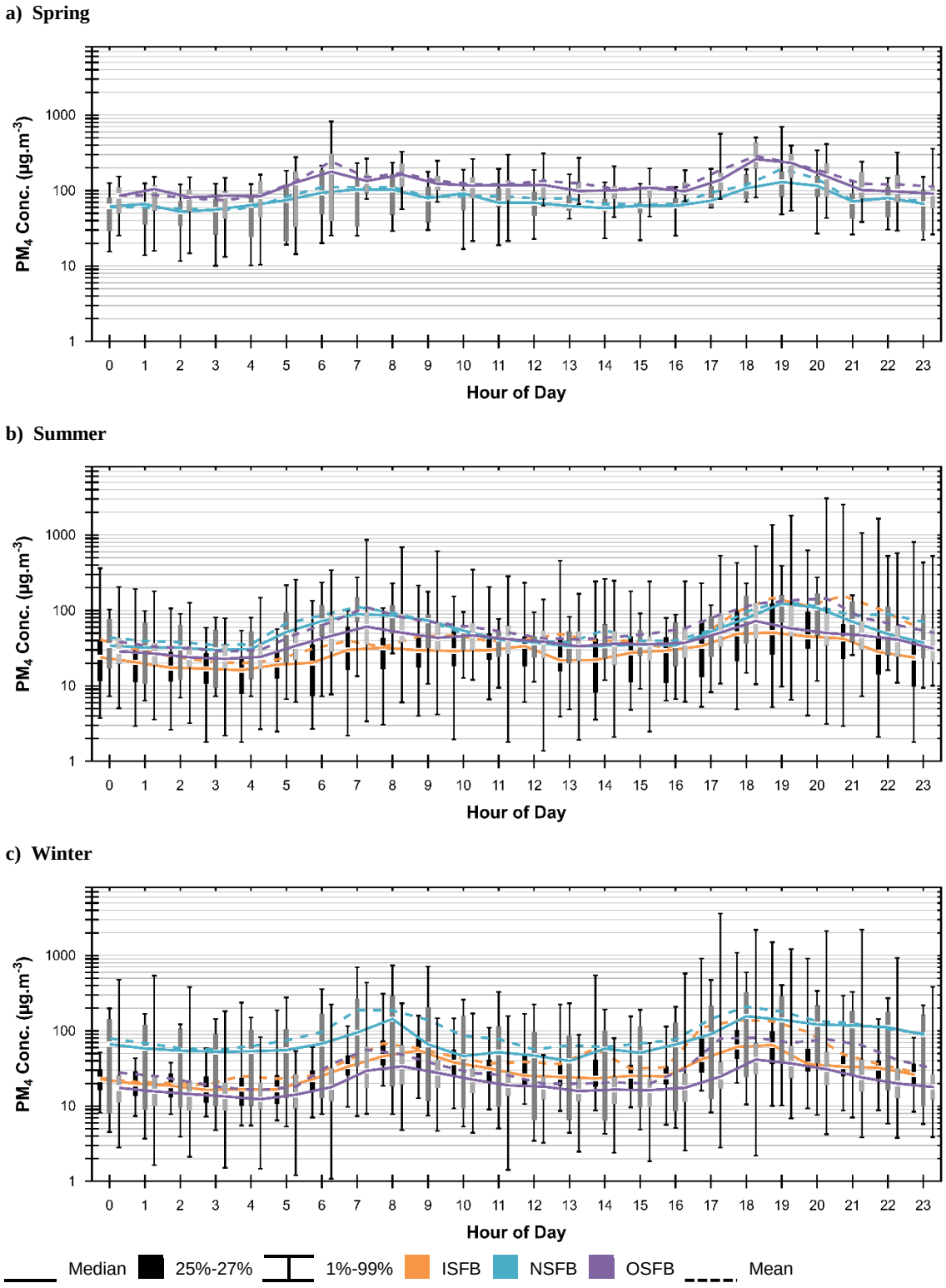

Figure 4.4 Box plots showing the spread and diurnal variation of the hourly averaged residential indoor PM_4, measured in the wood-burning communities of Agincourt and Giyani during a) spring, b) summer, and c) winter.

The day-night indoor PM_4 mass concentrations are investigated in the following section. The peaks are initiated earlier in the households that are primary sources of PM_4, like the ISFB. This further links indoor solid fuel burning the indoor PM_4 in households that do not burn solid fuel.

4.1.1.2. Daytime and night-time indoor PM_4 mass concentrations

The hourly averaged residential indoor PM_4 mass concentrations are used to investigate the day-night residential indoor PM_4 loadings. The daytime is represented by the hours of 07h00 to 17h00, while the night-time corresponds to the hours of 18h00 to 06h00. The mean (median) ±SD (IQR) [minimum-maximum] daytime and night-time indoor PM_4 loading was 118 (49) ±209 (94) [2-3610] $\mu g.m^{-3}$ and 113 (38) ±221 (77) [1-3065] $\mu g.m^{-3}$, respectively. The daytime PM_4 levels were on average a factor of 1.09 (1.11) ±0.05 times higher than during the daytime. The day-night variation in the indoor PM_4 loadings for the ISFB, NSFB, and OSFB households, categorised by season, are shown in *Figure 4.5*.

4.1.1.2.1. Household variations for the daytime and night-time PM_4

Based on the household solid fuel use classification *(Figure 4.5.a)* the day-night residential indoor PM_4 loadings are in the flowing order: ISFB > NSFB > OSFB. During the day the indoor PM_4 loadings in the ISFB (139 (47) ±325 (84) [2-5136] $\mu g.m^{-3}$) were 2.51 and 2.59 times higher than the NSFB (55 (32) ±87 (43) [1-1786] $\mu g.m^{-3}$) and OSFB (54 (30) ±111 (39) [1-3610] $\mu g.m^{-3}$) dwellings. The difference in the night-time concentrations were slightly less, with the ISFB (143 (36) ±418 (71) [1-6775] $\mu g.m^{-3}$) being a factor of 2.31 and 2.41 higher than the NSFB (62 (27) ±157 (47) [1-6910] $\mu g.m^{-3}$) and OSFB (60 (28) ±149 (38) [1-3067] $\mu g.m^{-3}$) households. There are more extreme (higher maximum) concentrations recorded during the night.

4.1.1.2.2. Seasonal variation of the daytime and night-time PM_4

During spring the day-night residential indoor PM_4 loadings *(Figure 4.5.b)* are in the flowing order: OSFB > ISFB > NSFB. During the day the indoor PM_4 loadings in the OSFB (134 (115) ±77 (67) [21-566] $\mu g.m^{-3}$) were 1.12 and 1.60 times higher than the ISFB (120 (69) ±181 (112) [2-1934] $\mu g.m^{-3}$) and OSFB (84 (69) ±50 (52) [17-236] $\mu g.m^{-3}$) dwellings. The difference in the night-time concentrations were slightly less, with the OSFB (142 (107) ±123 (113) [10-823] $\mu g.m^{-3}$) being a factor of 1.02 and 1.58 higher than the NSFB (138 (56) ±357 (80) [2-6775] $\mu g.m^{-3}$) and OSFB (90 (72) ±82 (80) [10-700] $\mu g.m^{-3}$) households. The PM_4 within the ISFB and OSFB are close to unity during the night-time. The night-time maximums in the ISFB, NSFB, and OSFB are factors of 3.50, 2.97, and 1.45 higher than those recorded during the day.

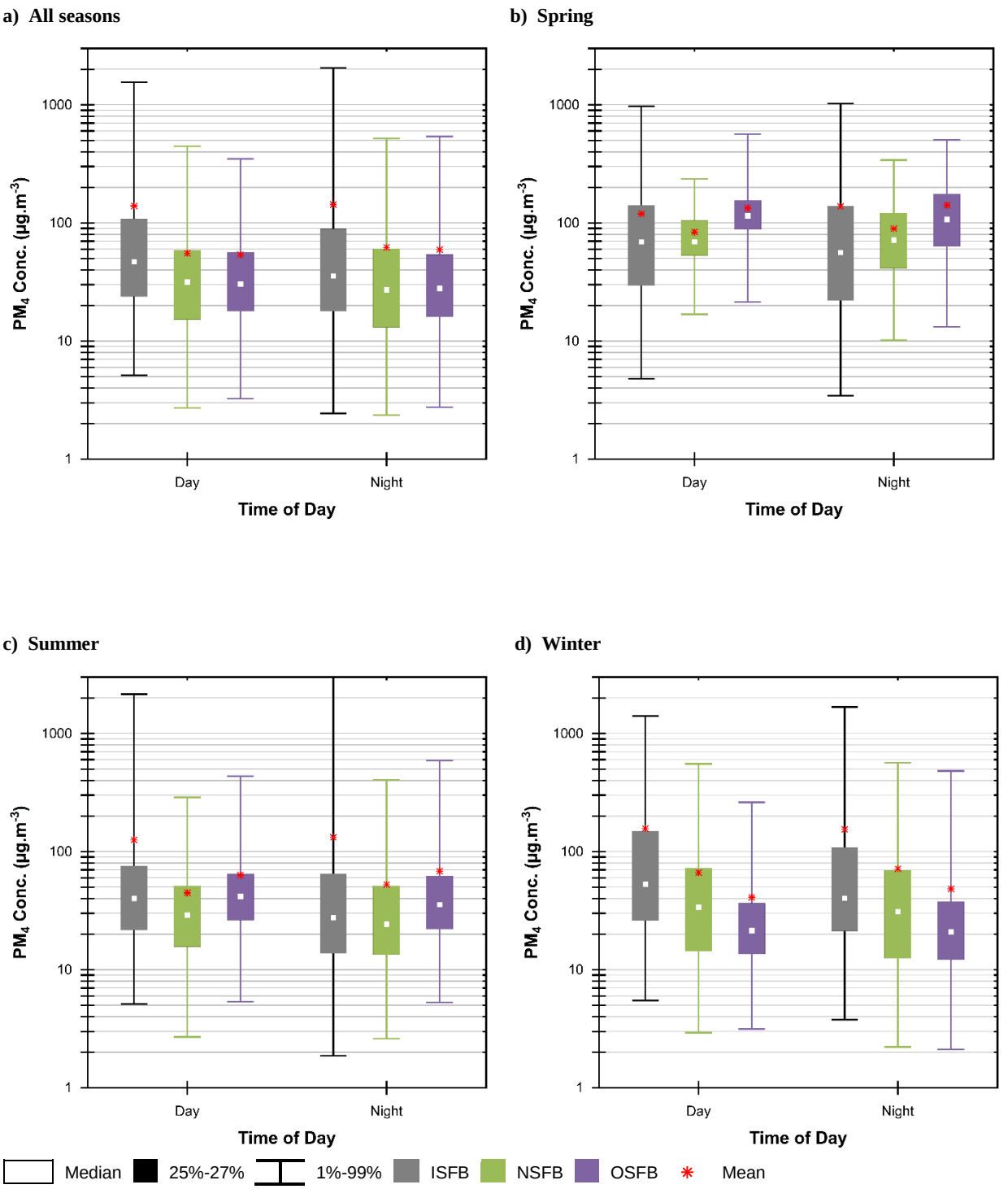

Figure 4.5 Box plots of the mean daytime (07h00 to 17h00) and night-time (18h00 to 06h00) hourly averaged PM_4 concentrations measured in the ISFB, NSFB, and OSFB for 2015 to 2017 during a) all seasons combined, b) spring, c) summer, and d) winter.

During summer the day-night residential indoor PM_4 loadings *(Figure 4.5.c)* are in the flowing order: ISFB > OSFB > NSFB. During the day the indoor PM_4 loadings in the ISFB (126 (40) ±390 (54) [2-5136] µg.m-

^{3}) were 1.99 and 2.81 times higher than the OSFB (63 (42) ±80 (39) [1-863] µg.m^{-3}) and NSFB (45 (29) ±61 (35) [1-894] µg.m^{-3}) dwellings. The difference in the night-time concentrations were slightly less, with the ISFB (132 (28) ±496 (52) [1-5561] µg.m^{-3}) being a factor of 1.93 and 2.52 higher than the OSFB (68 (36) ±157 (40) [2-3067] µg.m^{-3}) and NSFB (52 (24) ±183 (38) [1-6910] µg.m^{-3}) households. The night-time maximums in the ISFB, NSFB, and OSFB are factors of 1.08, 7.73, and 3.55 higher than those recorded during the day.

During winter the day-night residential indoor PM_4 loadings *(Figure 4.5.d)* are in the flowing order: ISFB > NSFB > OSFB. During the day the indoor PM_4 loadings in the ISFB (157 (53) ±278 (123) [2-3816] µg.m^{-3}) were 2.37 and 3.82 times higher than the NSFB (66 (34) ±108 (58) [2-1786] µg.m^{-3}) and OSFB (41 (22) ±61 (23) [1-3610] µg.m^{-3}) dwellings. The difference in the night-time concentrations were slightly less, with the ISFB (155 (40) ±342 (87) [1-4722] µg.m^{-3}) being a factor of 1.18 and 3.20 higher than the NSFB (71 (31) ±129 (57) [1-1906] µg.m^{-3}) and OSFB (48 (21) ±143 (26) [1-2207] µg.m^{-3}) households. The winter shows less variation in the difference between the maximum concentrations measured during day and night, compared to spring and summer.

The residential indoor PM_4 loadings were highest during the daytime (07h00 to 17h00) compared to the night-time (18h00 to 06h00), regardless of season and household fuel use classification. It is clear that there is less variation in the day-night difference in the ISFB, NSFB, and OSFB households during the winter, compared to summer and spring. This reduced variation during winter indicates that these household tend to have lower ventilation rates reducing the particulate loading inside the households. The reduces ventilations could be as a result of the local meteorological conditions experienced during winter, which include colder ambient temperatures and significantly reduced natural ventilation. This lowers the dispersion potential in the indoor-ambient environment.

The daily variation in the residential indoor PM_4 concentrations is considered in *Chapter 5 (see Section 0)*, where it is compared with the observed meteorological conditions. The following section investigates the variation in the daily averaged indoor $PM_{2.5}$ mass concentrations and how these compare to the WHO guidelines and NAAQS.

4.1.1.3. Indoor $PM_{2.5}$ exceedances of the 24-hr $PM_{2.5}$ NAAQS and WHO guidelines

The National Ambient Air Quality Standards (NAAQS) and the World Health Organisation (WHO) guidelines and standards have been discussed in detail in *Chapter 1 Section 1.2.3.2.1 (see Table 1.9)*. The 24-hour limit values set for the $PM_{2.5}$ size fraction are 40 and 25 µg.m^{-3} (4 allowable exceedances annually for the NAAQS), respectively.

The existing 5-min averaged PM_4 mass concentrations were converted to $PM_{2.5}$ by applying the 0.92 correction factor estimated in *Chapter 3 Section 3.3.3*. The 24-hour mean $PM_{2.5}$ mass concentrations were

calculated for days having ≥ 50% valid cases. These daily averages were compared to the NAAQS standards and WHO guidelines mentioned above. The United States Environmental Protections Agency (EPA) Air Quality Index (AQI) is also used as a reference index *(Table 4.1)*. A multilevel AQI was proposed for South Africa in 2012 and accepted in 2018, however, the US EPA AQI has an additional classification termed "Unhealthy for Sensitive" and is more clearly defined that the South African AQI. The number and percentage of exceedances are summarised in *Table 4.2*. The results are categorised by season, settlement and households fuel use.

Table 4.1 Air quality index for 24-hr averaged $PM_{2.5}$ mass concentrations in $\mu g.m^{-3}$ *(U.S.EPA, 2012)*

.Index No.	Levels of Health Concern	Air Quality Index	Description	$PM_{2.5}$ ($\mu g.m^{-3}$)
1	Low	0-50	Air quality is considered satisfactory, and air pollution poses little or no risk.	0.0-12.0
2	Moderate	51-100	Air quality is acceptable; however, for some pollutants, there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.	12.1-35.4
3	Unhealthy for Sensitive	101-150	Members of sensitive groups may experience health effects. The general public is not likely to be affected.	35.5-55.4
4	Unhealthy	151-200	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.	55.5-150.4
5	Very Unhealthy	201-300	Health alert: everyone may experience more serious health effects.	150.5-250.4
6	Hazardous	301-500	Health warnings of emergency conditions. The entire population is more likely to be affected.	≥250.5

A total of one-thousand-eight-hundred-and-nineteen (1819) 24-hr averaged indoor $PM_{2.5}$ measurements were valid for the comparison. It was found that 1036 (~57%) and 1382 (~76%) of the residential indoor $PM_{2.5}$ daily averages were above the 40 $\mu g.m^{-3}$ NAAQS and 25 $\mu g.m^{-3}$ WHO guideline, respectively.

There were a total of 127 (~6%), 896 (~49%), and 796 (~44%) 24-hr averaged indoor $PM_{2.5}$ measurements, respectively for spring, summer and winter. During spring, the NAAQS and WHO guidelines were exceeded for 94 (~74%) and 109 (~86%) of the daily averages. While during summer, the NAAQS and WHO guidelines were exceeded for 452 (~50%) and 663 (~86%) of the daily averages. The NAAQS and WHO guidelines were exceeded for 487 (~61%) and 610 (~77%) of the daily averages recoded during winter. The small sample size for the spring has the potential to skew the overall comparison thus, it is excluded from the overall seasonal ranking of exceedences experienced, which is as follow: winter > summer.

The box-plots of the 24-hr averaged indoor $PM_{2.5}$ mass concentrations for individual households sampled in the various settlements across the twenty-one (21) sampling campaigns are presented in *Figure 4.6* to

Figure 4.10. The exceedances will be discussed based on the community, settlement, season, and household fuel use.

4.1.1.3.1. Exceedances of 24-hr $PM_{2.5}$ NAAQS and WHO guidelines within the coal-burning communities

KwaDela

In summer 2014 *(Figure 4.6.b)* and 2015 *(Figure 4.6.d)*, it was found that 54 and 50% of the indoor $PM_{2.5}$ daily averages were above the NAAQS 40 µg.m^{-3} limit, respectively, while 78 and 70% of the daily averages exceeded the WHO guideline of 25 µg.m^{-3}. The ISFB households exceeded the NAAQS and WHO guideline during 2014 (67 and 88 %) and 2015 (47 and 67 %). However, the NSFB dwelling exceedances were very different as 2014 (14 and 57%) had only a small percentage of NAAQS and WHO guideline exceedances compared to 2015 (62 and 82 %).

During the summer the ISFB houses with the highest summer mean (median) ±SD (IQR) [minimum-maximum] 24-hr average indoor $PM_{2.5}$ concentrations were H002 with 420 (354) ±190 (250) [278-695] µg.m^{-3} and H023 with 206 (155) ±185 (185) [29-667] µg.m^{-3} during 2014 and 2015, respectively. Meaning, that even during summer periods these households experience particulate air pollution which is considered very unhealthy and hazardous to human health. The ISFB dwellings with the lowest overall summer concentrations are H010 with 44 (45) ±16 (29) [25-65] µg.m^{-3} and 17 (17) ±5 (7) [6-26] µg.m^{-3} during 2014 and 2015, respectively, making it moderately unhealthy to unhealthy for groups of people who have preexisting conditions.

The NSFB dwellings with the highest summer mean 24-hr average indoor $PM_{2.5}$ concentrations were H006 with 28 (23) ±17 (15) [13-65] µg.m^{-3} and H003 with 67 (43) ±43 (62) [16-162] µg.m^{-3} during 2014 and 2015, respectively. Thus, residents were exposed to moderate to unhealthy particulate pollution levels. The houses with the lowest overall concentrations were H003 with 14 (15) ±3 (3) [10-16] µg.m^{-3} and H022 with 41 (41) ±17 (30) [10-75] µg.m^{-3} during 2014 and 2015, respectively.

On average, in KwaDela, 59 and 83 % of the indoor $PM_{2.5}$ daily averages were found to be above the NAAQS limit during winter 2013 *(Figure 4.6.a)* and winter 2014 *(Figure 4.6.c)*, respectively, while 78 and 93 % surpassed the WHO guideline. In 2013, the indoor solid fuel burning (ISFB) households were above the NAAQS and WHO guidelines for 60 and 78 % of the $PM_{2.5}$ daily averages, while for the non-solid fuel burning (NSFB) houses it was much lower at 0 and 100%, respectively. During 2014, the percentage NAAQS and WHO guideline exceedances were much higher the ISFB (88 and 94 %) and NSFB (71 and 95 %) dwellings.

The ISFB houses with the highest winter mean 24-hr average indoor $PM_{2.5}$ concentrations were H008 with 144 (135) ±57 (14) [82-237] µg.m^{-3} and H002 with 558 (544) ±193 (177) [259-914] µg.m^{-3} during 2013

and 2014, respectively. Meaning that these houses are constantly in a particulate air pollution state which is very unhealthy and hazardous to all the residents residing in these dwellings.

Table 4.2 Number (%) of 24-hr $PM_{2.5}$ NAAQS and WHO guideline exceedances recorded for the period 2013 to 2017 categorised by season, settlement, and household type.

Season	Settlement	House Type	Number of 24-hr samples	NAAQS Total N (%)	NAAQS N per year					WHO N (%)
					2013	2014	2015	2016	2017	
Spring	KwaZamokuhle	ISFB	103	70 (68)	-	-	70	-	-	85 (83)
	Giyani	NSFB	10	10 (100)	-	-	-	10	-	10 (100)
		OSFB	14	10 (100)	-	-	-	14	-	14 (100)
		Total	127	94 (74)	-	-	63	15	-	109 (86)
Summer	KwaDela	ISFB	282	151 (54)	-	63	88	-	-	210 (74)
		NSFB	104	46 (44)	-	2	44	-	-	71 (68)
	KwaZamokuhle	ISFB	210	111 (53)	-	-	-	88	23	164 (78)
		NSFB	27	21 (78)	-	-	-	-	21	26 (96)
	Jouberton	ISFB	5	0 (0)	-	-	-	-	0	0 (0)
		NSFB	86	28 (33)	-	-	-	20	8	47 (55)
	Agincourt	ISFB	32	9 (28)	-	-	-	7	2	18 (56)
		NSFB	13	8 (62)	-	-	-	-	8	10 (77)
		OSFB	93	37 (40)	-	-	-	29	8	73 (78)
	Giyani	NSFB	8	8 (100)	-	-	-	-	8	8 (100)
		OSFB	36	33 (92)	-	-	-	-	33	36 (100)
		Total	896	452 (50)	0	65	132	144	111	663 (86)
Winter	KwaDela	ISFB	233	176 (76)	85	91	-	-	-	205 (88)
		NSFB	87	54 (62)	4	50	-	-	-	73 (84)
	KwaZamokuhle	ISFB	177	173 (97)	-	-	15	146	12	177 (100)
		NSFB	15	9 (60)	-	-	-	-	9	12 (80)
	Jouberton	ISFB	11	2 (18)	-	-	-	0	2	7 (64)
		NSFB	88	31 (35)	-	-	-	10	21	51 (58
	Agincourt	ISFB	33	12 (36)	-	-	-	7	5	22 (67)
		NSFB	13	13 (100)	-	-	-	-	13	13 (100)
		OSFB	77	12 (16)	-	-	-	3	9	39 (51)
	Giyani	NSFB	8	0 (0)	-	-	-	-	0	1 (13)
		OSFB	39	5 (13)	-	-	-	-	5	10 (26)
		Total	796	487 (61)	89	141	15	166	76	610 (77)
Total (2013-2017)			**1819**	**1033 (57)**	**89**	**206**	**217**	**334**	**187**	**1382(76)**

The ISFB house with the lowest overall winter concentrations is H010 with 19 (19) ±5 (9) [10-28] and 32 (25) ±17 (13) [19-67] µg.m^{-3} during 2013 and 2014, respectively, making it moderately unhealthy to unhealthy for sensitive groups having preexisting conditions.

The NSFB dwelling with the highest winter mean 24-hr average indoor $PM_{2.5}$ concentration was H019 with 36 µg.m^{-3} and 103 (96) ±43 (63) [56-180] µg.m^{-3} during 2013 and 2014, respectively. Meaning the house almost always has an unhealthy level of particulate pollution during winter periods. The houses with the lowest overall concentrations were H003 with 30 (22) ±16 (13) [12-69] µg.m^{-3} and H006 with 55 (43) ±28 (30) [31-127] µg.m^{-3} during 2013 and 2014, respectively, making it unhealthy for sensitive groups.

The ISFB houses in KwaDela showed a higher inter-household variability, within a specific season, than the NSFB dwellings. Similarly, the ISFB houses had a higher intra-household variability when comparing summer and winter $PM_{2.5}$ measurements.

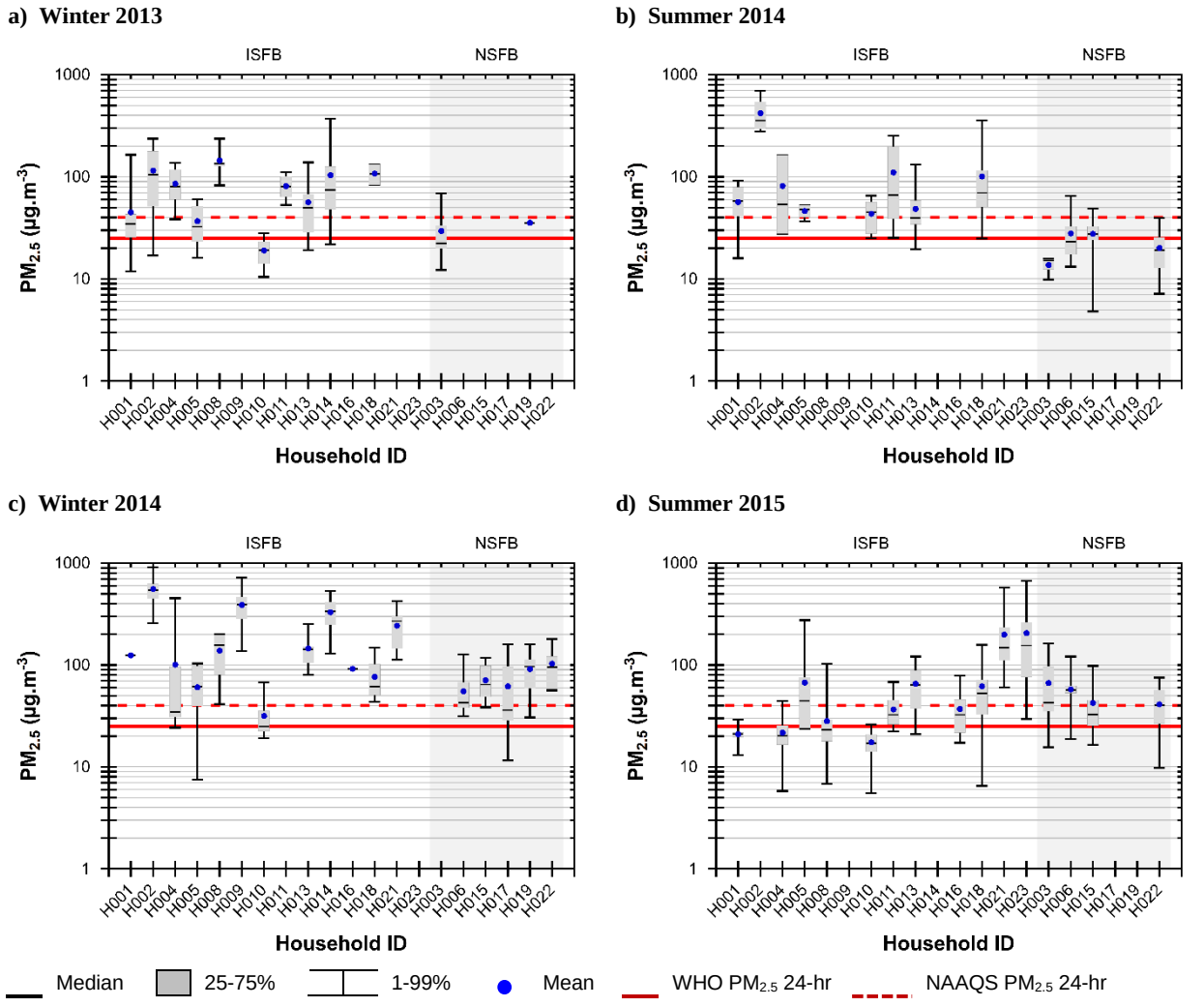

Figure 4.6 Box plots of the 24-hr averaged $PM_{2.5}$ concentrations compared to the WHO guideline (solid red line) and the NAAQS standard (stripped red line) in KwaDela for a) winter 2013, b) summer 2014, c) winter 2014, and d) summer 2015.

KwaZamokuhle

During the transitional spring period in 2015 *(Figure 4.7.b)*, 68 and 83% of the indoor $PM_{2.5}$ daily averages were above the NAAQS and WHO guidelines. Note that all the households sampled during this period were ISFB. The fine particulate concentrations had associated health risks ranging from low to hazardous. The house with the lowest mean 24-hr average indoor $PM_{2.5}$ concentration was H030 with 23 (23) ±10 (20) [13-33] $\mu g.m^{-3}$. The highest mean was recorded in H0.31 with 250 (200) ±166 (158) [66-746] $\mu g.m^{-3}$, thus being a factor of 10.96 higher than H027.

Similarly to the springtime, the daily means ranged from low to hazardous for human health. The ISFB dwelling with the lowest mean 24-hr averaged $PM_{2.5}$ concentrations during 2016 was H027 with 26 (24) ±12 (14) [8-65] $\mu g.m^{-3}$. The house with the highest overall mean during 2016 was H029 with 120 (88) ±87 (88) [27-430] $\mu g.m^{-3}$, thus it is higher than H026 by a factor of 4.67. The NSFB dwelling (H251), was sampled only during 2017. The concentration ranged from low to unhealthy, with a mean 24-hr indoor $PM_{2.5}$ loading of 49 (45) ±17 (18) [2-86] $\mu g.m^{-3}$. Compared to the ISFB (H024), sampled during the same period, which ranging from moderate to very unhealthy, with an average of 69 (61) ±39 (31) [20-202] $\mu g.m^{-3}$.

Winter experiences more extreme values. During winter 2015 *(Figure 4.7.a)*, 2016 *(Figure 4.7.d)*, and 2017 *(Figure 4.7.e)*, the 24-hr $PM_{2.5}$ NAAQS limit was exceeded for 100, 48, and 78 % of the recorded daily means. The WHO guideline exceedance occur for 100, 75, and 89% or the daily means during 2015, 2016 and 2017. Similarly to KwaDela, in winter, the 24-hr indoor $PM_{2.5}$ mass concentrations in the ISFB houses ranged from moderate to hazardous. The ISFB house with the lowest mean concentrations is H027 at 95 (102) ±35 (63) [38-142] $\mu g.m^{-3}$, H028 has the highest at 325 (312) ±139 (136) [159-525] $\mu g.m^{-3}$. Thus, H028 is a factor of 3.43 higher than H027. During 2017 the NSFB dwelling (H251) ranged from low to unhealthy, with a mean of 52 (59) ±24 (42) [13-88] $\mu g.m^{-3}$, $\mu g.m^{-3}$. The ISFB dwelling (H024), ranged from unhealthy for sensitive groups very unhealthy, with a mean of 100 (105) ±32 (42) [50-158] $\mu g.m^{-3}$. Thus, during winter the ISFB household experienced fine particulate loadings that were higher by a factor of 1.90 compared to the NSFB house.

The houses in KwaZamokuhle showed increased inter-household variability during the spring, compared to the summer and winter. The ISFB house exceeded the standard and guidelines more frequently than the NSFB dwelling.

On average, during summer 2016 *(Figure 4.7.c)* and 2017 *(Figure 4.7.f)*, the 24-hr $PM_{2.5}$ NAAQS limit was exceeded 48 and 81%, while the WHO guideline was surpassed by 75 and 96% of the daily $PM_{2.5}$ averages. Exceedances of 24-hr $PM_{2.5}$ NAAQS and WHO guidelines within the urban community

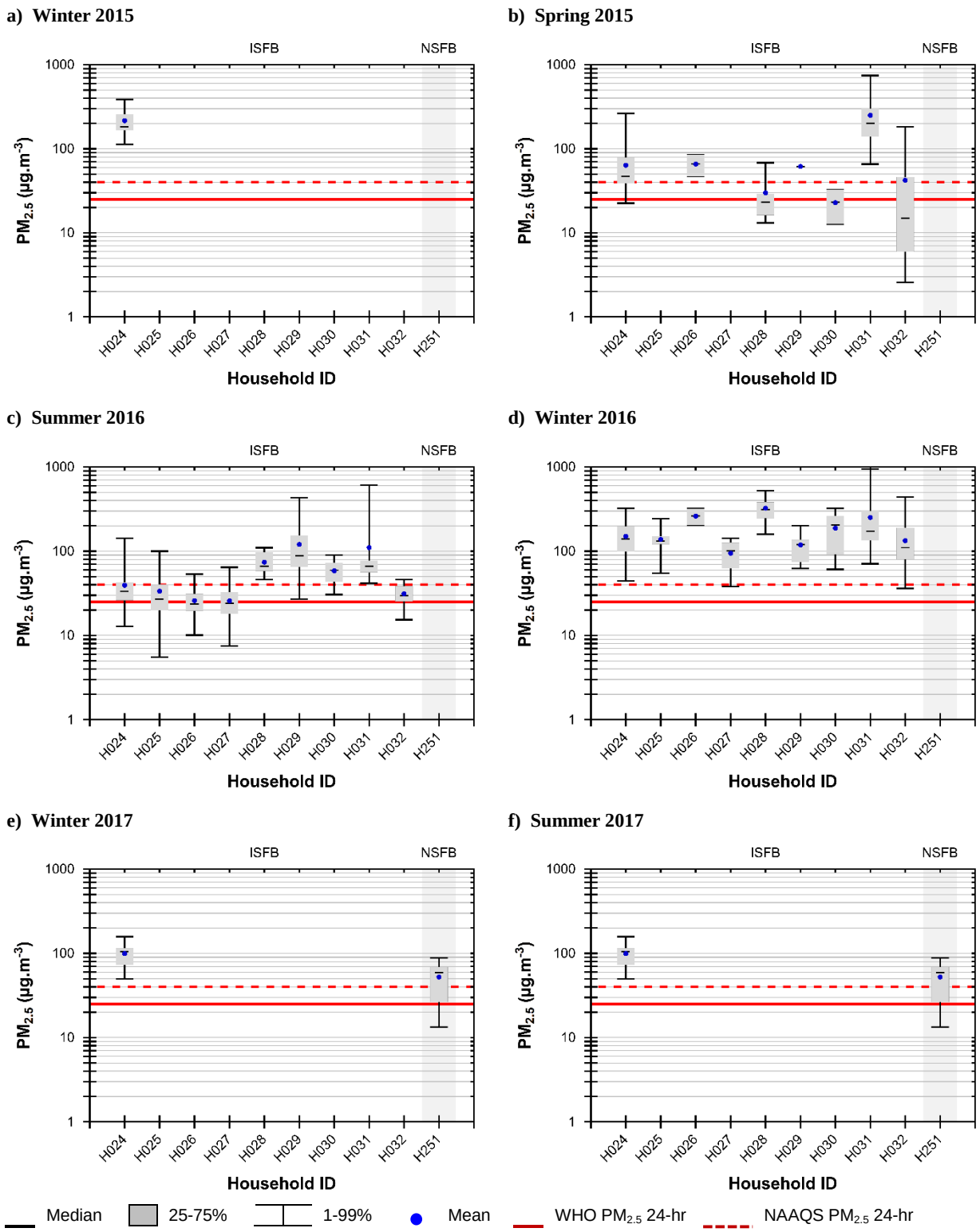

Figure 4.7 Box plots of the 24-hr averaged $PM_{2.5}$ concentrations compared to the WHO guideline (solid red line) and the NAAQS standard (stripped red line) in KwaZamokuhle for a) winter 2015, b) spring 2015, c) summer 2016, d) winter 2016, e) winter 2017, and f) summer 2017.

Jouberton

In summer 2016 *(Figure 4.8.a)* and 2017 *(Figure 4.8.c)*, it was found that 59 and 14% of the indoor $PM_{2.5}$ daily averages were above the NAAQS limit, respectively, while 85 and 26% exceeded the WHO guideline. Thus, the number of exceedences experienced during 2016 (20 NAAQS and 29 WHO guideline) and 2017 (8 NAAQS and 15 WHO guideline). The ISFB household sampled in 2017, showed no NAAQS or WHO guideline exceedences, while the NSFB dwellings exceeded 15 and 35% in 2017. The 24-hr indoor $PM_{2.5}$ mass concentrations in the ISFB house (H0225) was of low risk, mean concentration of 8 (7) ±2 (2) [5-9] $\mu g.m^{-3}$ during 2017.

In the NSFB dwellings, the 24-hr summer indoor $PM_{2.5}$ mass concentrations ranged from low to hazardous, with the lowest mean concentration occurring H160 with 27 (28) ±6 (13) [20-34] $\mu g.m^{-3}$ and H249 with 18 (18) ±8 (9) [8-30] $\mu g.m^{-3}$ during 2016 and 2017, respectively. The highest overall means were recorded for H151 with 143 (101) ±97 (86) [58-343] $\mu g.m^{-3}$ and H240 with 65 (68) ±21 (26) [38-90] $\mu g.m^{-3}$ during 2016 and 2017, respectively. Thus, the uppermost means were a factor of 5.29 (2016) and 3.69 (2017) higher than the lowest means.

On average, in Jouberton, 19 and 49% of the indoor $PM_{2.5}$ daily averages were found to be above the NAAQS limit during winter 2016 *(Figure 4.8.b)* and winter 2017 *(Figure 4.8.d)*, respectively, while 39 and 73% surpassed the WHO guideline.

The 24-hr winter indoor $PM_{2.5}$ mass concentrations in the ISFB houses ranged from low to unhealthy. There was only one ISFB house sampled during 2016 (H165) and 2017 (H225), respectively. The mean 24-hr average $PM_{2.5}$ concentrations for H165 and H225 were 25 (23) ±8 (10) [14-33] $\mu g.m^{-3}$ and 40 (36) ±17 (12) [24-71] $\mu g.m^{-3}$. The mean $PM_{2.5}$ loading in H225 was a factor of 1.60 higher than H165.

In the NSFB houses, the 24-hr winter indoor PM2.5 mass concentrations ranged from low to hazardous, with the lowest mean concentration being in H175 with 12 (13) ±6 (10) [6-19] µg.m-3 and H227 with 28 (26) ±8 (8) [22-42] µg.m-3 during 2016 and 2017, respectively. The highest overall means were recorded for H151 with 112 (118) ±67 (133) [42-175] µg.m-3 and H244 with 225 (241) ±88 (139) [124-329] µg.m-3 during 2016 and 2017, respectively. Thus, the uppermost means were a factor of 8.97 (2016) and 7.88 (2017) higher than the lowest means for the same period.

The houses in Jouberton showed a higher inter-household variability for each of the seasonal sampling campaigns. Jouberton also had a high seasonal variability in the number of exceedences experienced from one year to the next.

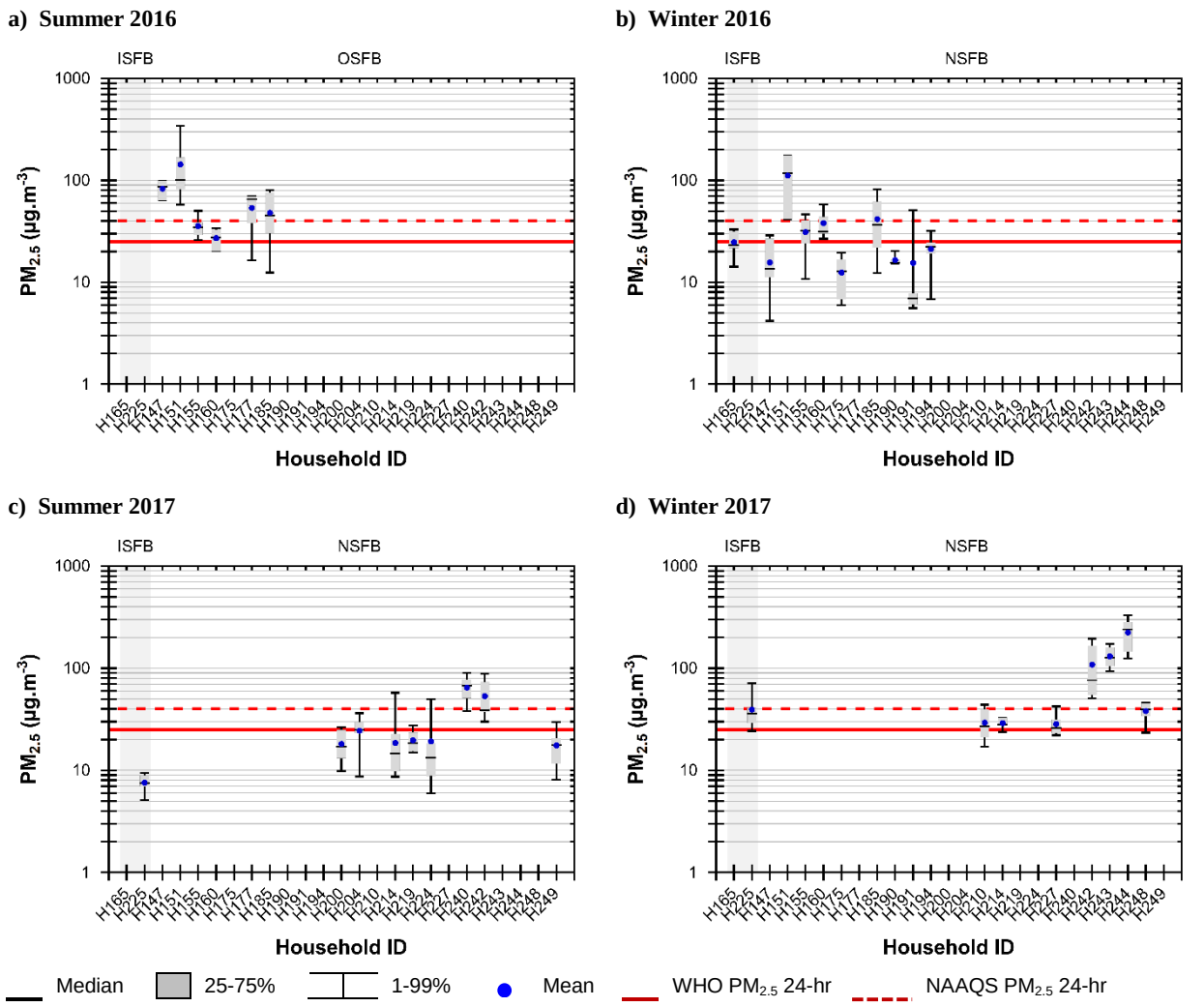

Figure 4.8 Box plots of the 24-hr averaged $PM_{2.5}$ concentrations compared to the WHO guideline (solid red line) and the NAAQS standard (stripped red line) in Jouberton for a) summer 2016, b) winter 2016, c) summer 2017, and d) winter 2017.

4.1.1.3.2. Exceedances of 24-hr $PM_{2.5}$ NAAQS and WHO guidelines within the wood-burning communities

Agincourt

In summer 2016 *(Figure 4.9.a)* and 2017 *(Figure 4.9.c)*, it was found that 51 and 27% of the indoor $PM_{2.5}$ daily averages were above the NAAQS limit, respectively, while 90 and 55% surpassed the WHO guideline. The number of exceedences experienced during 2017 (18 NAAQS and 37 WHO guideline exceedences) was significantly less than during 2016 (36 NAAQS and 64 WHO guideline exceedences). The ISFB households exceeded the NAAQS and WHO guideline 54 and 85% during 201, while in 2017 it was at 11 and 37%. The NSFB houses sampled during 2017 surpassed the NAAQS and WHO guideline for 62 and 77% of the daily means. The OSFB dwellings exceedances were 50 and 91% in 2016 compared to 23 and 57% in 2017.

The 24-hr summer indoor $PM_{2.5}$ mass concentrations in the ISFB houses ranged from low to hazardous, with the lowest mean 24-hr average $PM_{2.5}$ concentration in H062 with 27 (29) ±7 (10) [16-35] $\mu g.m^{-3}$ and H125 with 10 (10) ±4 (6) [5-14] $\mu g.m^{-3}$ during 2016 and 2017, respectively. While the highest were recorded in H043 with 124 (106) ±80 (121) [42-270] $\mu g.m^{-3}$ and H135 with 27 (27) ±7 (10) [14-37] $\mu g.m^{-3}$ during 2016 and 2017, respectively. The uppermost means were thus a factor of 4.68 (2016) and 2.85 (2017) higher than the lowest means for the same period.

In the NSFB houses, the 24-hr summer indoor $PM_{2.5}$ mass concentrations ranged from low to very unhealthy, with the lowest and highest overall mean 24-hr average concentrations were H115 with 32 (31) ±12 (18) [16-50] $\mu g.m^{-3}$ and H106 with 95 (83) ±40 (34) [65-173] $\mu g.m^{-3}$, respectively. The upper- and lowermost means differ by 63 $\mu g.m^{-3}$ (a factor of 3.02).

In the OSFB dwellings, the 24-hr summer indoor $PM_{2.5}$ mass concentrations ranged from low to hazardous, with the lowest mean occurring in H073 with 29 (30) ±7 (10) [19-36] $\mu g.m^{-3}$ and H095 with 23 (23) ±7 (7 [12-35] $\mu g.m^{-3}$ during 2016 and 2017, respectively. While the highest were recorded in H082 with 99 (60) ±128 (27) [25-414] $\mu g.m^{-3}$ and H117 with 104 (22) ±179 (167) [4-487] $\mu g.m^{-3}$ during 2016 and 2017, respectively. Thus, the uppermost means were a factor of 3.39 (2016) and 4.50 (2017) higher than the lowest means.

On average, in Agincourt, 17 and 43% of the indoor $PM_{2.5}$ daily averages were found to be above the NAAQS limit during winter 2016 *(Figure 4.9.b)* and winter 2017 *(Figure 4.9.d)*, respectively, while 47 and 73% surpassed the WHO guideline. In 2016, the ISFB households were above the NAAQS and WHO guidelines for 50 and 79 % of the $PM_{2.5}$ daily averages, while for the OSFB houses it was much lower at 7 and 37%, respectively. During 2017, the percentage NAAQS and WHO guideline exceedances were much lower for the ISFB (26 and 58%) and higher for the OSFB (29 and 71%) dwellings. The NSFB households exceeded both the standard and guideline for all days sampled.

The 24-hr winter indoor $PM_{2.5}$ mass concentrations in the ISFB houses ranged from moderate to unhealthy, with the lowest mean concentration in H062 with 47 (31) ±31 (39) [22-109] $\mu g.m^{-3}$ and H125 with 30 (29) ±13 (23) [15-48] $\mu g.m^{-3}$ during 2016 and 2017, respectively. While the highest were recorded in H043 with 69 (60) ±40 (79) [22-118] $\mu g.m^{-3}$ and H135 with 45 (31) ±37 (14) [25-128] $\mu g.m^{-3}$ during 2016 and 2017, respectively. The uppermost means were thus a factor of 1.48 (2016) and 1.49 (2017) higher than the lowest meant for the same period.

In the NSFB houses, the 24-hr winter indoor $PM_{2.5}$ mass concentrations ranged from unhealthy to very unhealthy, with the lowest- and highest mean concentration occurring in H106 with 108 (97) ±35 (69) [78-153] $\mu g.m^{-3}$ and H115 with 166 (169) ±49 (88) [96-240] $\mu g.m^{-3}$, respectively. The upper- and lowermost means differ by 58 $\mu g.m^{-3}$ (a factor of 1.53).

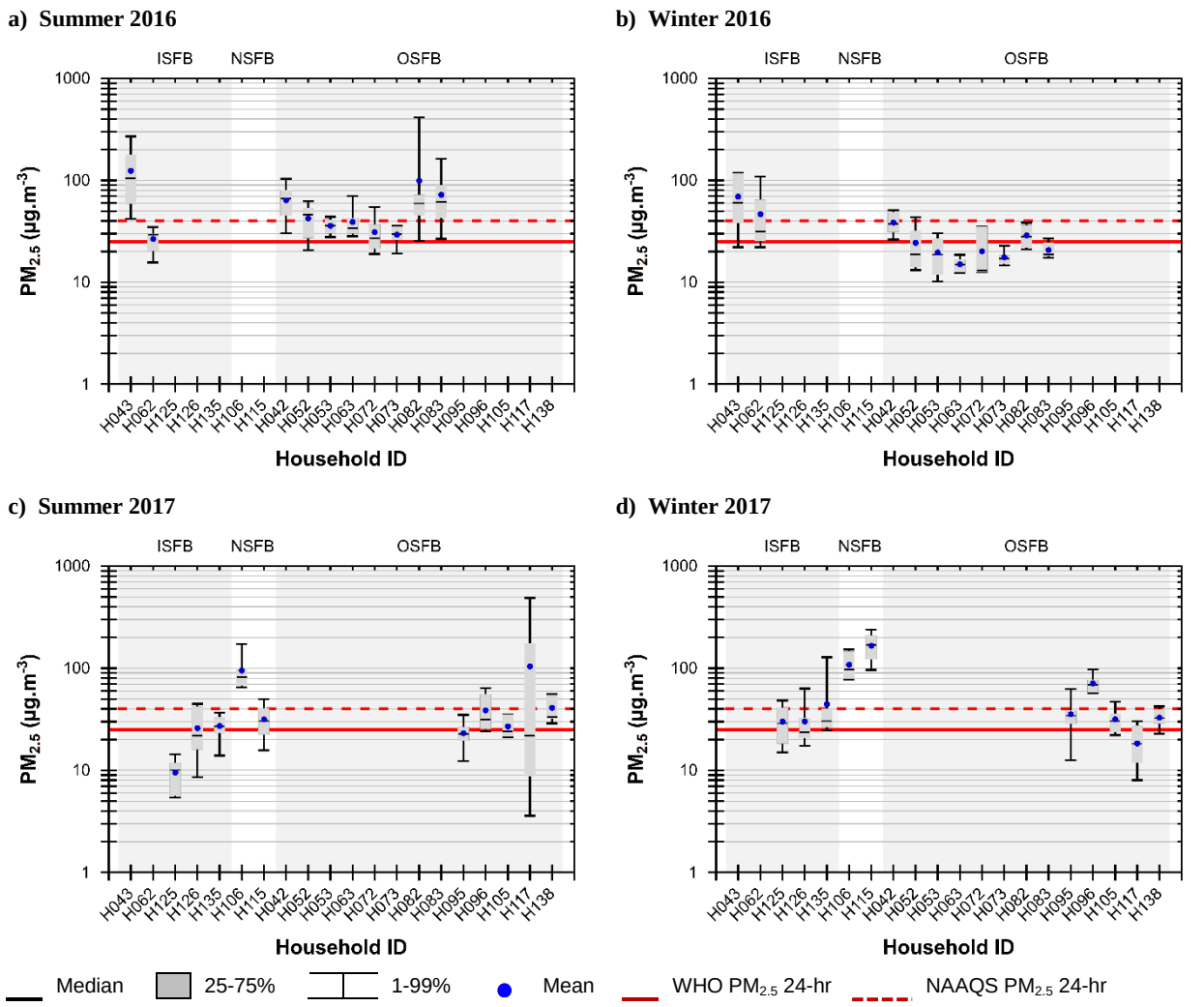

Figure 4.9 Box plots of the 24-hr averaged $PM_{2.5}$ concentrations compared to the WHO guideline (solid red line) and the NAAQS standard (stripped red line) in Agincourt for a) summer 2016, b) winter 2016, c) summer 2017, and d) winter 2017.

In the OSFB dwellings, the 24-hr winter indoor $PM_{2.5}$ mass concentrations ranged from low to unhealthy, with the lowest mean concentration occurring in H063 with 15 (15) ±2 (4) [12-19] µg.m^{-3} and H117 with 18 (18) ±8 (15) [8-30] µg.m^{-3} during 2016 and 2017, respectively. While the highest were recorded in H042 with 39 (37) ±10 (18) [26-51] µg.m^{-3} and H096 with 71 (69) ±16 (19) [57-97] µg.m^{-3} during 2016 and 2017, respectively. Thus, the uppermost means were a factor of 2.58 (2016) and 3.87 (2017) higher than the lowest mean.

Agincourt showed less inter household variability within a single seasonal sampling campaigns. Similarly, it experienced less intra-household variability from one season to the next, compared to the settlements within the coal-burning- and urbanised-communities.

Giyani

Throughout the 2016 spring period *(Figure 4.10.a)*, 100% (24 NAAQS and 24 WHO guideline exceedences) of the indoor $PM_{2.5}$ daily averages were above the NAAQS and WHO guidelines. The fine particulate concentrations had associated health risks ranging from moderate to unhealthy. The 24-hr indoor $PM_{2.5}$ mass concentrations in the NSFB house (H033) ranged from moderate to unhealthy, mean 24-hr concentration of 77 (73) ±37 (65 [41-144] $\mu g.m^{-3}$. In the OSFB dwellings ranged from moderate to unhealthy, with the lowest overall mean 24-hr average indoor $PM_{2.5}$ concentrations occurring in H035 with 68 (67) ±19 (31) [48-91] $\mu g.m^{-3}$. The highest mean was recorded in H034 with 149 (155) ±71 (126) [56-272] $\mu g.m^{-3}$, thus being a factor of 2.19 higher than H035. The houses showed less inter-household variability during spring when compared to the summer and winter periods.

On average, during summer 2017 *(Figure 4.10.b)* the 24-hr $PM_{2.5}$ NAAQS limit was exceeded 93%, while the WHO guideline was surpassed by 100% of the daily $PM_{2.5}$ averages (41 NAAQS and 44 WHO guideline exceedences). The NSFB households had NAAQS and WHO guideline exceedences of 100 %, while the OSFB dwellings exceeded 92 and 100% of the daily $PM_{2.5}$ average measurements. The NSFB (H033) dwelling had a 24-hr indoor $PM_{2.5}$ mass concentrations ranging from low to moderate, with a mean concentration of 74 (73) ±19 (20) [42-107] $\mu g.m^{-3}$. This house had similar levels of exposure during spring and summer. In the OSFB households ranged in health risks from low to unhealthy. The OSFB dwelling with the lowest mean 24-hr averaged indoor $PM_{2.5}$ concentrations was H037 with 43 (41) ±16 (16) [26-76] $\mu g.m^{-3}$. While the highest overall mean was recoded in H040 with 349 (244) ±283 (289) [152-754] $\mu g.m^{-3}$, thus it is higher than H037 by a factor of 8.12. This indicated a high inter-household variability in the OSFB dwellings during the summer.

During winter 2017 *(Figure 4.10.c)* the 24-hr $PM_{2.5}$ NAAQS limit was exceeded for 11% of the recorded daily means, while the WHO guideline was surpassed by 23% of daily $PM_{2.5}$ averages (5 NAAQS and 11 WHO guideline exceedences). This was significantly lower than those recorded during summer and spring. The fine particulate concentrations had associated health concerns ranging from low to hazardous. The NSFB households had NAAQS and WHO guideline exceedences of 0 and 13%, while the OSFB dwellings exceeded 13 and 26% of the daily $PM_{2.5}$ average measurements. The 24-hr indoor $PM_{2.5}$ mass concentrations in the NSFB house (H033) ranged from moderate to unhealthy, with mean concentration of 13 (11) ±7 (6) [8-28] $\mu g.m^{-3}$. This indicates that the summer and spring mean 24-hr mass concentrations were a factor of 5.69 higher than the winter. In the OSFB households, the lowest overall mean 24-hr averaged $PM_{2.5}$ concentrations was recorded in H034 with 13 (13) ±3 (4) [11-15] $\mu g.m^{-3}$ and the highest in H038 with 407 (160) ±487 (417) [56-1216] $\mu g.m^{-3}$. All the households sampled during the winter are comparable to H034, indicating that H038 might have a specific source which contributes to the increased level of fine particulate pollutions. The OSFB houses in Giyani had a higher seasonal intra- and inter-household variability compared to the NSFB dwellings.

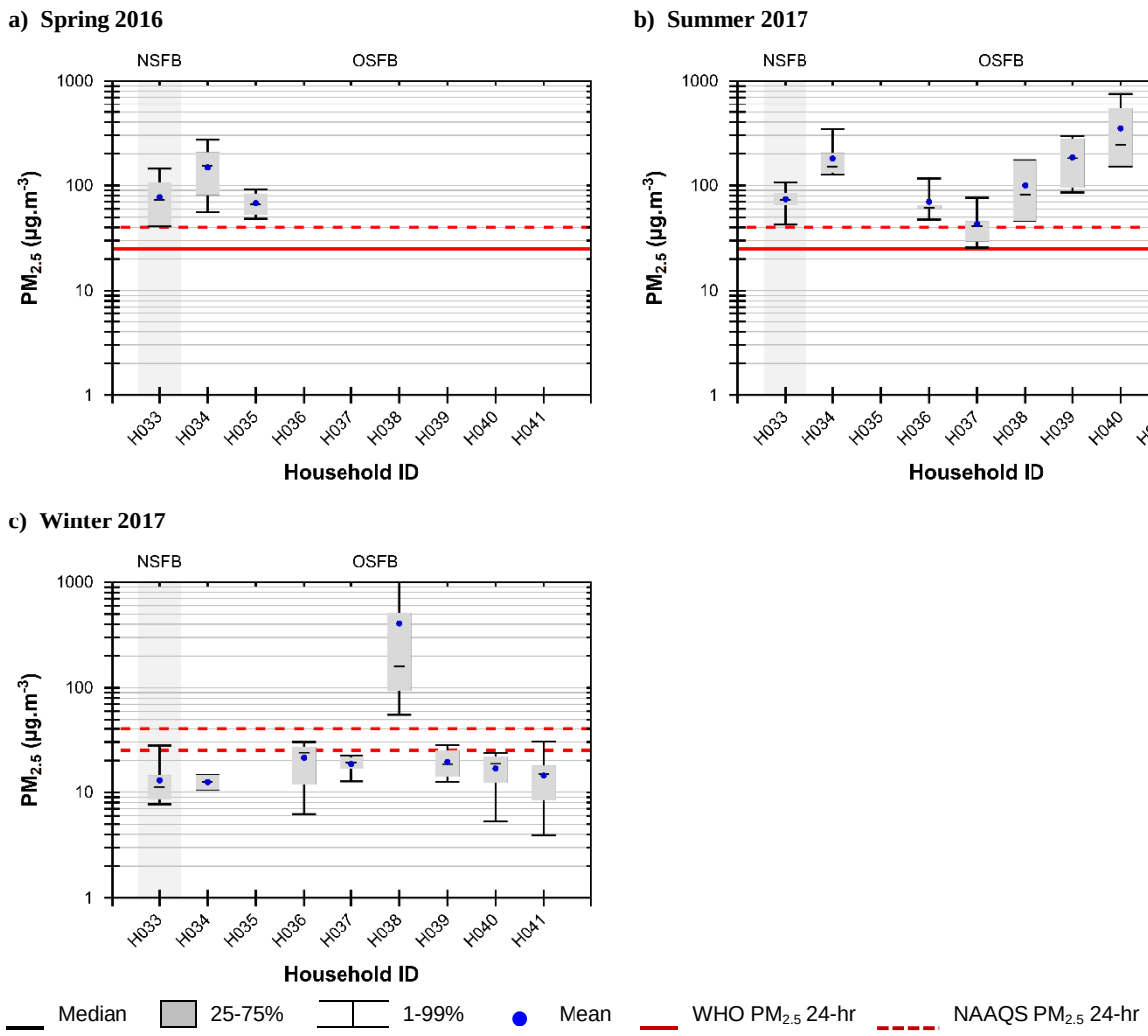

Figure 4.10 Box plots of the 24-hr averaged $PM_{2.5}$ concentrations compared to the WHO guideline (solid red line) and the NAAQS standard (stripped red line) in Giyani for a) spring 2016, b) summer 2017, and c) winter 2017.

The fact that so many of the households have high particulate concentrations, which are consistently exceeding standards and guidelines set for the ambient environment, informs the need for debate surrounding indoor particulate guidelines and/or standards. The proposed guidelines and/or standards should initially be set to that of the ambient environment as the impact pathways are the same for ambient and indoor exposure to particulate matter.

4.1.2. Source apportionment of residential indoor PM_4

Filters were collected in the residential indoor environment, across fifteen (15) sampling campaigns *(see Section 2.3.2.2.3),* between 1 February 2015 to 20 November 2017. The intermittent gravimetric sampling resulted in three-thousand-one-hundred-and-thirty (3130) samples collected. A total of two-thousand-eight-hundred-and-sixty-six (2866) valid exposed gravimetric PM_4 filter samples (91.57%) were collected, along with two-hundred-and-six (206) blanks (6.58%). The remaining filters were invalid due to i) damage

occurring during the offloading of the cassettes (1.69%), ii) sampling error (0.06%), and ii) misplaced filter cassettes (0.10%). The number of valid exposed filters are summarised in *Table 4.3*, where it is categorised by the community, settlement, household fuel use, season and year. There were a total of 389 (13.57%), 1156 (40.33%), and 1321 (16.09%) samples, respectively for the coal-burning-, urbanised-, and wood-burning communities. This included 646 (22.54%), 1234 (43.06%, and 986 (34.40%) samples, respectively for the ISFB, NSFB, and OSFB households.

The residential indoor PM_4 and associated trace element data are considered for the five settlements located within the coal-burning-, urbanised-, and wood-burning communities.

4.1.2.1. Gravimetric indoor PM_4 mass concentrations

The mean (±SD) particulate- and inorganic trace element mass concentrations ($\mu g.m^{-3}$) for the residential indoor PM_4 are summarised in *Table C.1* in *Appendix C*. The mean (median) ±SD (IQR) [minimum-maximum] residential indoor PM_4 mass concentrations for the five low-income settlements sampled in this study was 84 (64) ±125 (72) [1-4201] $\mu g.m^{-3}$. Similarly to the continuous PM_4, the mean gravimetric indoor PM_4 for the community classification was in the following order: coal > wood > urban. The coal-burning communities had the highest mean indoor PM_4 at 126 (72) ±171 (87) [1-1447] $\mu g.m^{-3}$. It was a factor of 1.68 and 1.57 higher than the urban- (75 (60) ±138 (65) [1-4201] $\mu g.m^{-3}$) and outside wood-burning (80 (64) ±90 (79) [1-1132] $\mu g.m^{-3}$) communities, respectively *(Figure 4.11)*.

Table 4.3 Exposed filters collected categorised by community, settlement, season, and household fuel use.

Community	Settlement	Fuel Use	Total N	Spring	Summer			Winter		
				2016	2015	2016	2017	2015	2016	2017
Coal	KwaDela	ISFB	144	-	144	-	-	-	-	-
	KwaZamokuhle	ISFB	180	-	-	-	36	93	-	51
		NSFB	65	-	-	-	37	-	-	28
		Total	**389**	**-**	**144**	**-**	**73**	**93**	**-**	**79**
Urban	Jouberton	ISFB	129	-	-	28	42	-	24	35
		NSFB	1027	-	-	279	221	-	273	254
		Total	**1156**	**-**	**-**	**307**	**263**	**-**	**297**	**289**
Wood	Agincourt	ISFB	190	-	-	39	57	-	42	52
		NSFB	126	-	-	28	38	-	28	32
		OSFB	895	-	-	236	204	-	253	202
	Giyani	ISFB	3	3	-	-	-	-	-	-
		NSFB	16	3	-	-	7	-	-	6
		OSFB	91	3	-	-	45	-	-	43
		Total	**1321**	**9**	**-**	**303**	**351**	**-**	**323**	**335**
		Total	**2866**	**9**	**144**	**610**	**687**	**93**	**620**	**703**

Settlement variations of gravimetric PM_4 mass concentration

The individual settlements had varying levels of particulate pollution. The gravimetric indoor PM_4 concentrations within the five settlements were in the following order: KwaZamokuhle > KwaDela > Giyani > Agincourt > Jouberton. The coal-burning settlement of KwaZamokuhle (139 (86) ±160 (107) [1-820] $\mu g.m^{-3}$) had the highest mean indoor PM_4. It was a factor of 1.34 higher than the second coal-burning settlement of KwaDela (104 (58) ±188 (51) [4-1447] $\mu g.m^{-3}$). The largest variation was between KwaZamokuhle and Jouberton (75 (60) ±138 (65) [1-4201] $\mu g.m^{-3}$) as the urban settlement was a factor of 0.54 lower than the coal-burning. The wood-burning settlements of Agincourt (80 (64) ±85 (79) [1-1132] $\mu g.m^{-3}$) and Giyani (87 (48) ±131 (74) [3-917] $\mu g.m^{-3}$) were factors of 0.57 and 0.63 lower than KwaZamokuhle.

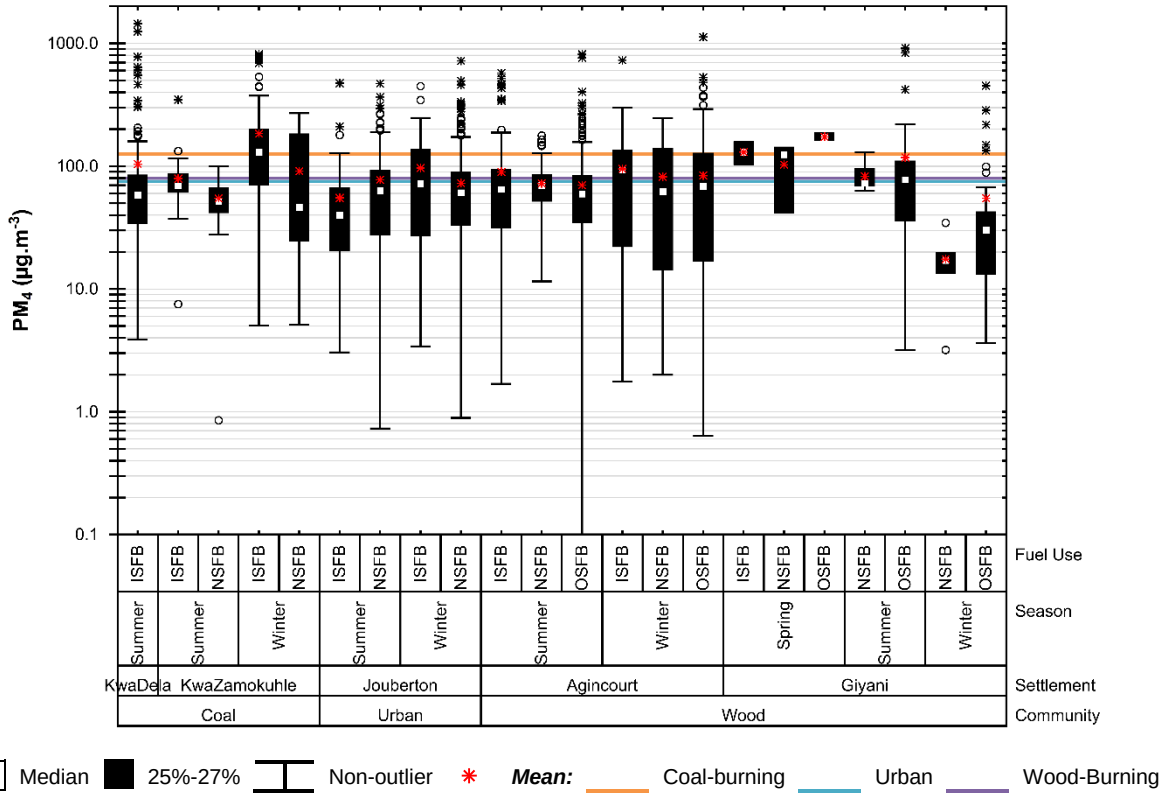

Figure 4.11 Variability box plots of the mean gravimetric PM_4 mass concentrations ($\mu g.m^{-3}$) measured in the residential indoor environments of low-income settlement in South Africa between 2015 and 2017, categorised by community, settlement, season, and household fuel use.

Seasonal variations of gravimetric PM_4 mass concentration

The seasonally categorised spread of the gravimetrically measured residential indoor PM_4 within each settlement was considered. The mean summer concentration in KwaDela was 104 (58) ±188 (51) [4-1447] $\mu g.m^{-3}$. In the second coal-burning community of KwaZamokuhle the mean summer and winter loadings wee 67 (63) ±41 (31) [1-349] $\mu g.m^{-3}$ and 169 (119) ±180 (145) [5-820] $\mu g.m^{-3}$, respectively. The winter

particulate loadings in KwaZamokuhle were a factor of 2.53 higher than during summer. The summer PM_4 levels were higher (factor of 1.55) in KwaDela than KwaZamokuhle.

In the urban settlement of Jouberton, the mean indoor PM_4 levels for summer (75 (59) ±182 (66) [1-4201] $\mu g.m^{-3}$) and winter (75 (61) ±71 (51) [1-720] $\mu g.m^{-3}$) were close to unity. The summer loadings in Jouberton ranged between those recorded in KwaDela and KwaZamokuhle, whereas the winter level was a factor of 0.44 lower than in KwaZamokuhle.

The outside wood-burning settlement of Agincourt experienced similar summer (74 (61) ±81 (50) [1-821] $\mu g.m^{-3}$) particulate loadings to that Jouberton. The winter loadings in Agincourt were slightly higher (factor of 1.16) than the summer at 85 (71) ±89 (112) [1-1132] $\mu g.m^{-3}$. Similarly to Jouberton, the winter loadings in Agincourt were a factor of 0.50 lower than in KwaZamokuhle. The particulate loadings in Giyani are very different to that of the other settlements. The spring period has the highest mean PM_4 level at 136 (141) ±43 (40) [42-185] $\mu g.m^{-3}$, followed by summer (113 (74) ±917 (62) [3-917] $\mu g.m^{-3}$) and winter (50 (29) ±79 (25) [3-452] $\mu g.m^{-3}$). Thus, Giyani had the lowest mean particulate loading during winter (factor of 0.30 to 0.59) compared to the other settlement.

Household variations of gravimetric PM_4 mass concentration

Based on the household fuel use classification the mean continuous indoor PM_4 was in the following order: indoor solid fuel burning (ISFB) > outdoor solid fuel burning (OSFB) > non-solid fuel burning (NSFB). The ISFB dwellings had a mean indoor PM_4 loading of 111 (72) ±148 (89) [2-1447] $\mu g.m^{-3}$. This was a factor of 1.49 and 1.42 higher than the NSFB (75 (62) ±133 (62) [1-4201] $\mu g.m^{-3}$) and OSFB (78 (60) ±91 (78) [1-986] $\mu g.m^{-3}$) households.

The variability in the mean indoor PM_4 for households, categorised by community type, settlement, season, and household fuel use *(Figure 4.11)* follows the same trend as described for the overall seasonal order, where the ISFB > OSFB > NSFB. The only settlements showing a variation from the above was in Jouberton during summer (NSFB > ISFB by a factor of 1.40) and in Giyani during spring (OSFB > ISFB by a factor of 1.33).

4.1.2.2. Elemental mass concentration characterisation of indoor PM_4

The chemical composition of atmospheric aerosols is necessary to clarify the likely sources impacting on the specific receptors, in this case, the residential indoor environments of homes situated within low-income settlement across South Africa. The elemental concentrations ($\mu g.m^{-3}$) associated with the residential indoor PM_4 measured within the low-income settlements were derived by wavelength dispersive x-ray fluorescence (WD-XRF) as discussed in *Chapter 2, Section 0*. Twenty (20) of the measured elements were included in the final source apportionment analysis. These elements included Na, Mg, Al, Si, P, S, Cl, K,

Ca, Ti, V, Cr, Mn, Fe, Cu, Zn, Br, Sn, Ba, and Pb. The mean (±SD) element mass concentrations associated with the residential indoor PM_4, categorised by community, settlement, season, and household fuel use are summarised in *Table C.1* in *Appendix C*. The variation in the abundance of the element concentrations and loadings are investigate based on the above categorisation.

The mean concentrations for the detected and discussed elements within the residential indoor environment within low-income settlement was 33.47 µg.m^{-3}, which was ~40% of the mean PM_4 loading *(Figure D.1.d)*. The remaining unaccounted for fraction of the PM_4 could be attributed to undetected elemental and soluble inorganic components, as well as, the carbonaceous species. The most abundant detected elements *(Figure 4.12)*, each accounting for 5 to <10% of PM_4, was Si and Na. The second group of elements, each accounting between 1 to <3% of the PM_4, included Al, Ca, Pb, Zn, Cl, Cu, Fe, Ba, Mg, Sn, K, and S. The third group of elements, each contributing between 0.1 and <1 to the PM_4, included Cr, V, Ti, and Mn. The fourth group of elements, each contributing to <0.1% of the PM_4 loading, included Br and P.

The significance of each element as a source contributor, based on its abundance, is an important aspect to consider when interpreting qualitative source apportionment by PCA. Based on the reviewed literature *(see Table 1.3 in Chapter 1 Section 1.2.1.2.1)* the significance of the above mentioned elements as primary- (≥10%), secondary- (1.0 to <10%), tertiary- (0.1 to <1%) and minor- (<0.1%) source contributors to fine fraction particulate matter, are as follow:

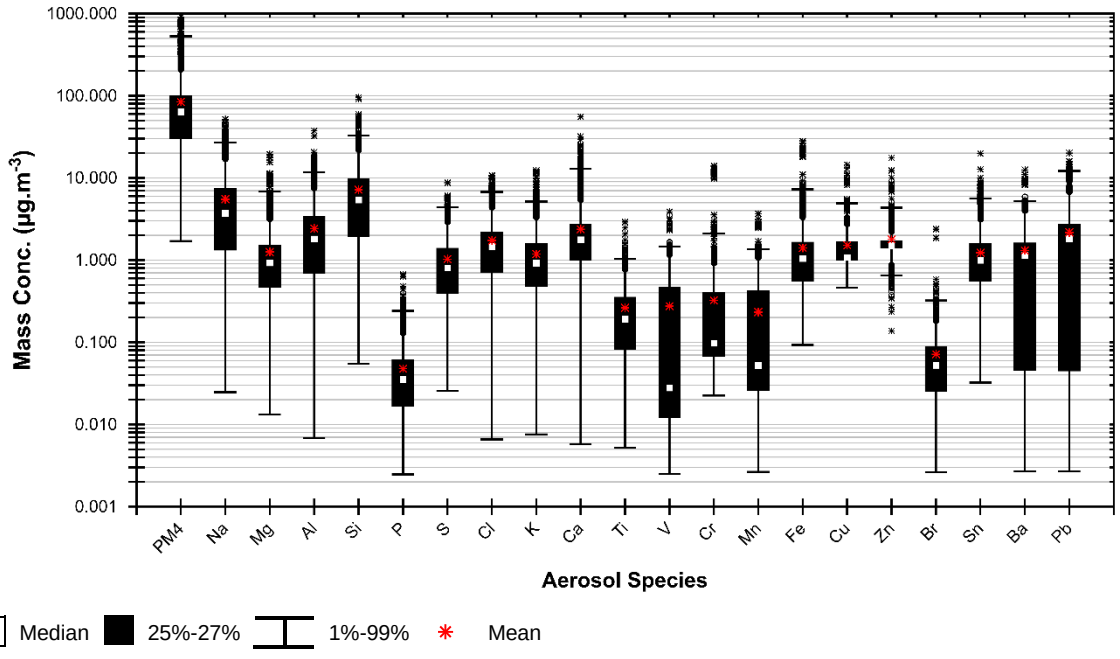

Figure 4.12 Box plots of the mean PM_4- and element mass concentrations (µg.m^{-3}) measured in the residential indoor environments of low-income settlement in South Africa between 2015 and 2017.

Silicon (Si) was the most abundant detected element with a mean (median) ±SD (IQR) [min-max] concentration of 7.24 (5.41) ±7.55 (8.01) [<0.01-95.87] µg.m^{-3}. Within the indoor environment of the low-

income settlements, it accounts for 8.59% of the total PM_4. It is a primary contributor to sources that are linked to crustal material. This includes for instance agricultural related activities resulting in the resuspension of soil as well as unpaved road dust. In addition, as a secondary contributor, it could be related to road traffic sources such as brake- and paved road dust. At the tertiary level, it is related to combustion waste burning and gasoline vehicle emission. Furthermore, it is a minor contributor to residential coal- and wood combustion.

Sodium (Na) was the second most abundant detected element, contributing to 6.56% of PM_4, with a mean concentration of 5.53 (3.71) ±5.90 (6.29) [<0.01-52.02] $\mu g.m^{-3}$. It is a primary contributor to marine salt, while as a secondary contributor it is related to crustal material, heavy motor vehicle emissions, and construction dust. On a tertiary level, it contributes to tobacco, residential solid fuel combustion activities (coal and wood), paved road traffic emission, tire dust, alternative residential combustion such as liquid petroleum gas (LPG) and kerosene. Also, it is a minor contributor to unpaved road dust.

Aluminium (Al) contributed to 2.89% of the PM_4 with a mean concentrations of 2.43 (1.82) ±2.56 (2.74) [<0.01-37.37] $\mu g.m^{-3}$. It is a secondary contributor to crustal material related sources (soil, unpaved- and paved roads), coal combustion, tire dust, and tobacco. As a tertiary level, it is found in sources such as marine salt, brake dust, paved road traffic emission, gasoline vehicle emission, and waste burning activities. In addition, it acts as a minor contributor to residential solid fuel combustion (wood and coal) and diesel vehicle emissions.

Calcium (Ca) had a mean concentration of 2.38 (1.78) ±2.76 (1.78) [<0.01-55.73] $\mu g.m^{-3}$ and makes up approximately 2.82% of the PM_4 mass. It is a primary contributor to dust-related sources such as paved- and unpaved roads, cement, and construction work. It acts as a secondary contributor to crustal material related sources, traffic emissions, and tobacco. At a tertiary level, it contributes to marine salt, brake dust, gasoline vehicle emissions, and waste burning. Furthermore, it is a minor contributor to biomass burning, residential solid fuel combustion, as well as diesel- and heavy vehicle emissions

Lead (Pb) contributed to 2.58% of the PM_4 with a mean concentrations of 2.18 (1.83) ±2.88 (2.70) [<0.01-20.15] $\mu g.m^{-3}$. It is a significant tertiary contributor toward traffic relates sources such as gasoline- and diesel vehicles, brake dust, and tire wear. In addition, it also contributes to crustal material and waster burning. At a minor level, it is related to various residential combustion activities, biomass burning, and tobacco.

Zinc (Zn) had a mean concentration of 1.80 (1.51) ±0.95 (0.34) [0.14-17.61] $\mu g.m^{-3}$, and contributed to 2.14% of the PM_4. Contributes to numerous sources at a tertiary level, this includes crustal material, residential solid fuel combustion, waste burning, and vehicle emission. Furthermore, it is a minor contributor to biomass burning, tobacco, traffic emissions, as well as paved- and unpaved roads.

Chlorine (Cl) contributed to 2.06% of the PM_4 with and mean concentration of 1.73 (1.46) ±1.45 (1.48) [<0.01-10.82] $\mu g.m^{-3}$. It is a primary contributor to marine salt while it acts a secondary toward vegetative burning. It is a tertiary contributor to sources such as crustal material, gasoline motor vehicle emissions, and tire dust. Furthermore, it contributes small quantities to unpaved roads.

Copper (Cu) had a mean contraction of 1.52 (1.08) ±1.12 (0.71) [0.09-14.53] $\mu g.m^{-3}$, contributing to 1.80% of the PM_4. It acts as a secondary contributor to sources such as brake dust and at a tertiary level, it is linked to coal combustion and marine salt. It is a minor contributor toward crustal material, residential combustion activities, vehicle emission, ire dust, tobacco, traffic emission, and waste burning.

Iron (Fe) makes up about 1.67% of the PM4 with a mean concentration of 1.40 (1.05) ±1.97 (1.11) [0.03-28.04] $\mu g.m^{-3}$. It is a primary contributor toward brake dust and unpaved roads. At a secondary level, it contributes to crustal material, coal combustion, construction dust, tire dust and tobacco. Also, it is a minor contributor in coal-stove, LPG-, and wood-stove combustion.

Barium (Ba) had a mean indoor concentration of Ba (1.31 (1.15) ±1.60 (1.59) [<0.01-12.59] $\mu g.m^{-3}$. It made up about 1.56% of the PM_4 mass. At a secondary level, it contributes to brake dust, while it is related to marine salt, agricultural soil, and tire wear at a tertiary level. Also, it is a minor contributor to residential solid fuel use, biomass burning, waste burning, and traffic emissions.

Magnesium (Mg) contributed to about 1.49% of the particulate mass, with a mean concentration of 1.26 (0.93) ±1.39 (1.59) [<0.01-19.52] $\mu g.m^{-3}$. Mg is not a primary contributor, however, at a secondary level, it is found in sources such as crustal material, marine salt, and construction dust. It is a tertiary contributor to brake and tire dust, as well as residential solid fuel combustion. Also, it is a minor contributor to alternative combustion activities (kerosene and LPG), vehicle- and traffic emission, as well as wood- and waste burning.

Tin (Sn) had a mean concentration of 1.24 (1.00) ±1.13 (1.04) [<0.01-19.91] $\mu g.m^{-3}$, contributing to 1.47% of the PM_4 mass. It is a secondary contributor to waste burning, while at a minor level it is linked to crustal material, marine salt, tire wear, and wood combustion.

Potassium (K) account for approximately 1.41% of the PM4 mass and had a mean concentration of 1.19 (0.92) ±1.11 (1.14) [<0.01-12.34] $\mu g.m^{-3}$. At a secondary level it is mainly related to combustion (coal/wood) and burning (biomass/waste) activates. It also contributed to unpaved road dust. However, on a tertiary level, it was related to road-, vehicle-, and traffic emission.

Sulphur (S) had a mean concentration of 1.03 (0.81) ±0.92 (1.01) [<0.01-8.77] $\mu g.m^{-3}$, contributing to 1.22% of the PM_4 mass. It acts as a secondary contributor to combustion-related activities and vehicle

emission. It is linked, at a tertiary level, to crustal material, biomass burning, and residential solid fuel combustion. Also, it is a minor contributor to dust and municipal waste burning.

Chromium (Cr) made up about 0.38% of the PM_4 mass, with a mean concentration of 0.32 (0.10) ±0.94 (0.34) [<0.01-14.12] $\mu g.m^{-3}$. It contributes, at a tertiary level, to residential solid fuel combustion and paved road dust. Furthermore, it is a minor contributor to crustal material, marine salt, road traffic- and vehicle emissions, tobacco, and waste burning.

Vanadium (V) had a mean concentration of 0.28 (0.03) ±0.43 (0.46) [<0.01-3.89] $\mu g.m^{-3}$, contributing to 0.33% of the PM_4. It is a secondary contributor to fuel oil burning while contributing to coal combustion on a tertiary level. At the minor level, it contributes to crustal material, residential combustion activities, road traffic- and vehicle emissions, paved-and unpaved road dust, tobacco, and waste burning.

Titanium (Ti) accounted for 0.31% of the PM4, with a mean concentration of 0.26 (0.19) ±0.25 (0.28) [<0.01-2.92] $\mu g.m^{-3}$. It is linked, at a secondary level, with brake- and tire dust and to crustal material as a tertiary contributor. Also, it is a minor contributor to marine salt, residential fuel combustion, unpaved roads, and waste burning.

Manganese (Mn) had a mean concentration of 0.23 (0.05) ±0.38 (0.41) [<0.01-3.68] $\mu g.m^{-3}$, accounting for 0.28% of the PM_4 mass. It acts mostly as a tertiary or minor contributor. It is related, as a tertiary contributor, to crustal material and road traffic sources. At a minor level, it contributes toward marine salt, biomass burning, various combustion-related activities, tire dust, tobacco, and waste burning.

Phosphorus (P) is the second least abundant element with a mean concentration of 0.05 (0.04) ±0.05 (0.05) [<0.01-0.67] $\mu g.m^{-3}$, contributing to 0.06% of the PM_4. It mainly acts as a tertiary and minor source contributor. At a tertiary level, it is linked to gasoline vehicle emission, coal combustion, and unpaved road dust. Whereas, at a minor level it is connected to wood combustion, paved road dust, as well as municipal- and garden waster burning.

Bromine (Br) was the least abundant within the PM_4 loading as is contributed to 0.08% of the mass, with a mean concentration of 0.07 (0.05) ±0.10 (0.06) [<0.01-2.39] $\mu g.m^{-3}$. It contributes to waste burning at a secondary level. At a tertiary contributor, it is related to gasoline vehicle emission, while it is connected to biomass burning and unpaved roads at a minor level.

Community-to-community ratios of elemental mass concentrations

The community-to-community ratios of the elemental mass concentrations are used to evaluate whether there are obvious differences in the mean indoor PM_4 elemental mass concentrations measured within the

coal-burning- (Coal), urbanised- (Urban), and wood-burning (Wood) communities *(Figure 4.13)*. Ratios that were >0.90 and <1.10 were considered close to unity.

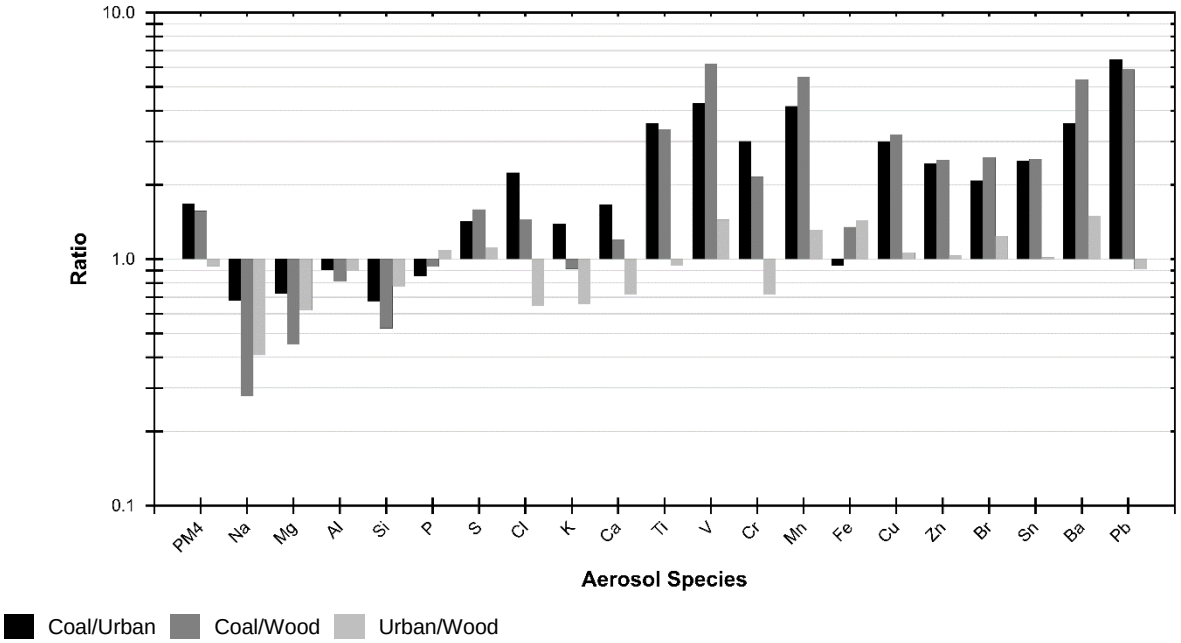

Figure 4.13 Community-to-community ratios of mean elemental mass concentrations of the measured PM_4 measured the residential indoor environment of low-income settlements within South Africa between 2015 and 2017.

The Coal/Urban community ratios indicate that the PM_4 loading was higher in the coal-burning community. Al and Fe were close to unity in both communities, while Na (ratio: 0.68), Mg (ratio: 0.72), Si (ratio: 0.68) and P (ratio: 0.85) mass concentrations were more prominent in the urban community. The elements associated with various anthropogenic activities are elevated in the coal-burning community by ratios ranging between 1.39 for K to 6.47 for Pb.

The Coal/Wood community ratios have a similar profile to that of the Coal/Urban ratios, however, there are noticeable differences for specific elements. The PM_4 loading was higher in the coal-burning community. P and K had ratios close to unity in both communities, while Na (ratio: 0.28), Mg (ratio: 0.45), Al (ratio: 0.81) and Si (ratio: 0.52) mass concentrations were higher in the wood-burning communities. The remaining elements, associated mostly with anthropogenic activities, were elevated in the coal-burning communities by ratios ranging between 1.20 for Ca to 6.22 for V.

The Urban/Wood community ratios are significantly different from those observed for the Coal/Urban and Coal/Wood comparisons. The PM_4 mass concentrations for the urbanised and wood-burning communities were close to unity. A number of elements (Al, P, Ti, Cu, Zn, Sn, and Pb) were close to unity, indicating that these elements had similar loadings in both communities. However, Na (ratio: 0.41), Mg (ratio: 0.62), Si (ratio: 0.78), Cl (ratio: 0.65), K (ratio: 0.66), Ca (ratio: 0.72), and Cr (ratio: 0.72) loadings were more

prevalent in the wood-burning communities. While the elements related to anthropogenic sources experienced higher loadings in the urban community which included S (ratio: 1.12), V (ratio: 1.44), Mn (ratio: 1.32), Fe (ratio: 1.44), Br (ratio: 1.24), and Ba (ratio: 1.50).

The abundance- and relationship of the elemental mass concentrations are dependent on the contributing sources during the time of sampling. Thus, the specific geographic location and time of sampling (season) will have an impact on the elemental characterisation and subsequent qualitative source identification.

The average percentage abundance of elements categorised by community, settlement, season and household fuel use is summarised in *Table 4.4*.

Table 4.4 Average elemental contributions (%), per element, to the residential indoor PM_4 loadings categorised by community, settlement, season and household solid fuel use.

Settlement	Season	Fuel Use	Percentage (%) of measured PM_4						
			<0.1	**0.1 to 1**	**1 to < 3**	**3 to <5**	**5 to <10**	**≥ 10**	**Det.**
Coal-burning Communities									
KwaDela	Summer	ISFB	Al, P	Na, Mg, Si, K, Ti	S, Ca, V, Cr, Mn, Fe	Zn, Sn	Cl, Cu, Ba, Pb		38
KwaZamokuhle	Summer	ISFB	P, V	Cl, Cr, Mn, Br, Ba	S, K, Ti, Fe	Na, Cu, Zn, Sn	Al, Ca	Si	65
		NSFB	P, V, Cr, Mn	Mg, Cl, Br, Ba	Na, Al, S, K, Ca, Ti, Fe	Si, Cu, Zn, Sn	-	Pb	63
	Winter	ISFB	P	Ti, V, Cr, Mn	Mg, S, Cl, K, Fe, Sn	Na, Al, Ca, Cu, Zn, Ba	Si, Pb	-	25
		NSFB	P, V, Mn	Mg, Ti, Cr, Br, Ba	Na, Al, S, Cl, K, Ca, Fe, Cu, Sn	Zn	Si, Pb	-	32
Summer			P	Mg, K, Ti, Cr	Na, Al, Si, S, V, Mn, Fe	Cl, Ca, Cu, Zn, Sn, Ba	Pb	-	46
Winter			P, Br	Ti, V, Cr, Mn, Fe	Na, Al, S, Cl, K, Ca, Cu, Zn, Sn, Ba, Pb	Si	-	-	26
Coal-burning Community			P	Mg, Ti, V, Cr, Mn, Br	Na, Al, S, Cl, K, Fe, Sn	Si, Ca, Cu, Zn	Pb		34
Urbanised Community									
Jouberton	Summer	ISFB	P, Br	Mg, K, Ti, V, Cr, Mn	Al, S, Cl, Ca, Fe, Cu, Zn, Sn, Ba, Pb	Na	Si	-	44
		NSFB	P, Br	Ti, V, Cr, Mn	Mg, Al, S< Cl, K, Ca, Fe, Cu, Zn, Sn, Ba, Pb	Na	Si	-	37
	Winter	ISFB	P, V, Mn, Br, Ba, Pb	Mg, Ti, Cr	Al, S, Cl, K, Ca, Fe, Cu, Zn, Sn	Na	Si	-	24
		NSFB	P, V, Mn, Br, Ba, Pb	S, Ti, Cr	Mg, Al, Cl, K, Ca, Fe, Cu, Zn, Sn	Na	Si	-	33
Summer			P, Br	Ti, V, Cr, Mn	Mg, Al, S, Cl, K, Fe, Cu, Zn, Sn, Ba, Pb	Na, Ca	Si	-	38
Winter			P, V, Mn, Ba, Pb	S, Ti, Cr, Br	Mg, Cl, K, Ca, Fe, Cu, Zn, Sn	Na, Al	Si	-	32
Urban Community			P, Br	Ti, V, Cr, Mn	Mg, Al, S, Cl, K, Ca, Fe, Cu, Zn, Sn, Ba, Pb	Na	Si		36

Table 4.4 (Continues)

Settlement	Season	Fuel Use	Percentage of PM_4						
			<0.1	**0.1 to 1**	**1 to < 3**	**3 to <5**	**5 to <10**	**≥ 10**	**Det.**
Wood-burning Communities									
Agincourt	Summer	ISFB	P, V, Mn, Br, Ba	Ti, Cr, Fe, Pb	Mg, Al, Cl, K, Cu, Zn, Sn	Ca	Na, Si	-	27
		NSFB	P, V, Mn, Br, Ba, Pb	S, Ti, Cr, Fe	Mg, Al, Cl, K, Ca, Cu, Zn, Sn	-	Na, Si	-	34
		OSFB	P, V, Mn, Br, Ba	S, Ti, Cr, Fe, Pb	Mg, Al, Cl, K, Ca, Cu, Zn, Sn	-	Na, Si	-	33
	Winter	ISFB	P, Br	Ti, V, Cr, Mn	Mg, S, Cl, K, Fe, Cu, Zn, Sn, Ba, Pb	Al, Ca	-	Na, Si	52
		NSFB	P, Br	Ti, V, Cr, Mn	Mg, S, Cl, K, Fe, Cu, Zn, Sn, Ba, Pb	Al, Ca	-	Na, Si	59
		OSFB	P, Br	Ti, V, Cr, Mn	Mg, S, Cl, K, Fe, Cu, Zn, Sn, Ba, Pb	Al, Ca	-	Na, Si	55
Giyani	Spring	ISFB	V. Cr, Mn, Br, Ba	P, Ti	Al, S, Cl, Ca, Fe, Cu, Zn, Sn	Mg, K, Pb	Na, Si	-	26
		NSFB	V, Mn, Br, Ba	P, Ti, Cr	S, Cl, Cu, Zn, Sn, Pb	Al, K, Ca, Fe	Na, Mg	Si	41
		OSFB	V, Br, Ba	P, Ti, Cr, Mn, Sn	S, Cl, Cu, Zn	K, Ca, Pb	Na, Mg, Al, Fe	Si	34
	Summer	NSFB	P, V, Cr, Mn, Br, Ba	Al, S, K, Ti, Fe	Mg, Si, Cl, Ca, Cu, Zn, Sn, Pb	-	Na	-	24
		OSFB	P, V, Mn, Ba	Mg, Al, S, K, Ti	Si, Cl, Ca, Cu, Zn, Sn, Pb	Na, Fe	-	-	18
	Winter	NSFB	P, V, Cr, Mn, Br, Ba	S, K, Ti	Mg, Al, Cl, Ca, Fe, Cu, Zn, Sn	Na, Si, Pb	-	-	100
		OSFB	V, Cr, Mn, Br, Ba	P, Ti	Mg, S, Cl, K, Fe, Cu, Zn, Sn, Pb	Al, Ca	Na	Si	77
Spring			P, V, Cr, Mn, Br, Ba	S, Cl, Ti, Cu, Sn	Al, K, Ca, Fe, Zn, Pb	Na, Mg	Si	-	33
Summer			P, V, Mn, Br, Ba	S, Ti, Cr, Pb	Mg, Al, Cl, K, Ca, Fe, Cu, Zn, Sn	-	Na, Si	-	30
Winter			P, Br	Ti, V, Cr, Mn	Mg, S, Cl, K, Fe, Cu, Zn, Sn, Ba, Pb	Al, Ca	-	Si	56
Wood-burning Communities			P, Br	Ti, V, Cr, Mn, Ba	Mg, S, Cl, K, Fe, Cu, Zn, Sn, Pb	Al, Ca	Na	Si	44
Residential Indoor			P, Br	Ti, V, Cr, Mn	Mg, Al, S, Cl, K, Ca, Fe, Cu, Zn, Sn, Ba, Pb		Na, Si		40

The abundance of each element, in percentages, were divided into six (6) groups, namely i) <0.1, ii) 0.1 to < 1, iii) 1 to < 3, iv) 3 to <5, v) 5 to <10, and vi) ≥10. These results are investigated further in the following Sections *4.1.2.2.1, 4.1.2.2.2*, and *4.1.2.2.3*.

4.1.2.2.1. Elemental mass concentrations within the coal-burning communities

The mean concentrations for the detected and discussed elements in the residential indoor environment within the coal-burning communities were 42.95 µg.m^{-3}, which was ~34% of the mean PM_4 loading *(Table 4.4* and *Figure D.2.d)*. The most abundant detected elements, accounting for >10% of PM_4, was Pb. The second group of elements, each accounting between 3 to <5% of the PM_4, included Si, Ca, Cu, and Zn. The third group of elements, each contributing between 1 and <3 %to the PM_4, included Na, Al, S, Cl, K, Fe, and Sn. The fourth group of elements, each contributing between 0.1 and 1% to the PM_4 loading, included Mg, Ti, V, Cr, Mn, and Br. The least prominent element was P, contributing <0.1% of the total PM_4 mass.

The high concentration of lead (Pb) in the coal-burning communities, vary from the observation made within the urbanise- and wood-burning communities. This indicates that there is an amalgamation of sources contributing specifically to Pb. These sources could include a variety of combustion- (coal, kerosene, waste, diesel, gasoline, LPG) and road traffic emission (tire ware, brake dust, etc.). In smaller quantities it can be caused by environmental tobacco smoke and biomass burning.

Season-to-season ratios of elemental mass concentrations within the coal-burning communities

The summer-to-winter ratios are used to evaluate whether there are seasonal differences in the mean indoor PM_4 elemental mass concentrations measured within the coal-burning communities *(Figure 4.14)*. The winter experienced a higher mean PM_4 mass loading compared to summer (ratio: 0.54). The mean summer concentrations for the detected and discussed elements was 41.76 µg.m^{-3}, which was ~46% of the mean PM_4 loading *(Figure D.3.d)*. The winter mean for the detected and discussed elements was similar and at 43.73 µg.m^{-3}, however, it only accounted for ~26% of the mean collected PM_4 mass *(Figure D.4.d)*. The Fe and Zn elements were close to unity, thus indicated similar mean mass loading during both summer and winter. Elements such as Cl (ratio: 1.36), Ti (ratio: 1.29), V (ratio: 2.13), Cr (ratio: 2.02), Mn (ratio: 2.17), Cu (ratio: 1.47), Ba (ratio: 1.67), and Pb (ratio: 1.2) experienced higher mass loadings during summer. The remaining elements, namely Na (ratio: 0.34), Mg (ratio: 0.65), Al (ratio: 0.33), Si (ratio: 0.36), P (ratio: 0.43), S (ratio: 0.45), K (ratio: 0.50), and Ca (ratio: 0.78) had higher winter loadings.

The elements that were close to unity (Fe and Zn) had similar mass concentrations, each accounting between 3 and 5% of the measured PM_4. This indicates that there is a constant ambient source contributing to these elements during both summer and winter.

The summer-to-winter ratios for the ISFB households showed a similar trend as the overall summer-to-winter comparison *(Figure 4.14)*. However, the summer-to-winter ratios for the NSFB households were slightly different as the majority of the elements showed less seasonal variation compared to the ISFB dwellings. Individual elements in the NSFB dwellings show significant seasonal variation. Cl (ratio: 0.15), Cr (ratio: 0.48), and Fe (ratio: 0.73) have higher winter loadings, while Cu (ratio: 1.45) and Pb (ratio: 2.58) show higher mass concentrations during the summer.

The ISFB households show less seasonal variability in the PM_4 element mass concentrations, indicating that these houses have similar sources contributing to the indoor PM_4 during both summer and winter. The NSFB households had increased seasonal variability associated with the detected element mass concentrations.

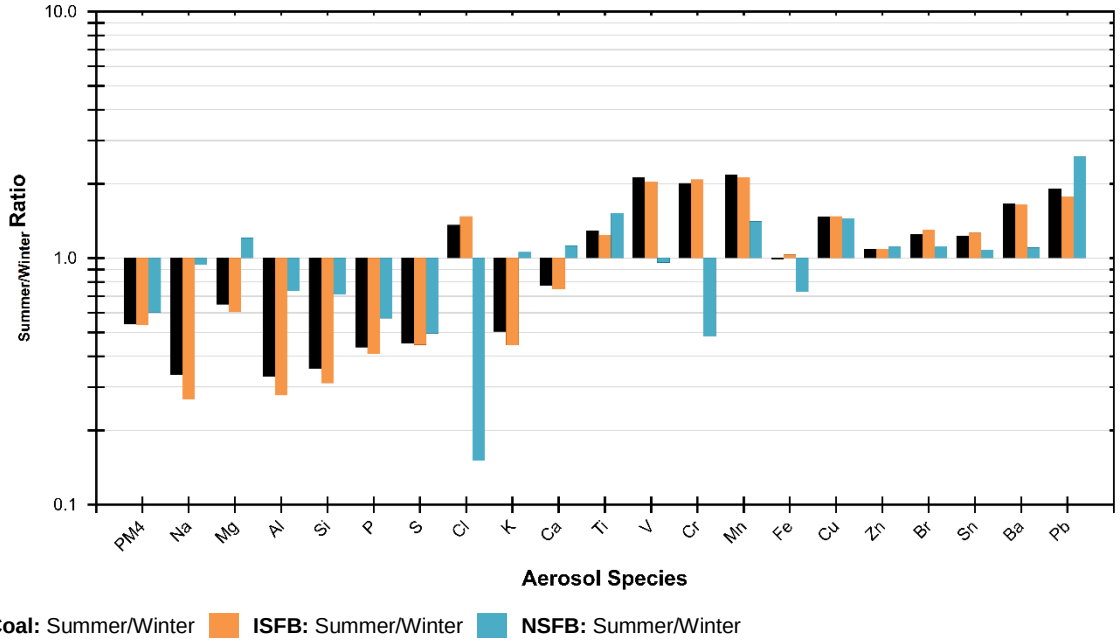

Figure 4.14 Summer-to-winter ratios of mean elemental mass concentrations of the measured PM_4 measured the residential indoor environment of coal-burning communities, categorised by ISFB- and NSFB households.

Household-to-household ratios of elemental mass concentrations within the coal-burning communities

The household-to-household ratios are used to evaluate whether there are differences in the detected element mass concentrations between houses, based on its fuel use classification, within the same season *(Figure 4.15)*.

The ISFB/NSFB ratios for the summer indicated that the ISFB has a higher PM_4 loading compared to the NSFB dwellings. Some elements (S, Br, Sn, and Pb) were close to unity indicating that these elements had similar mean loadings in both the ISFB and NSFB households during summer. Na (ratio: 0.5), Mg (ratio:

0.88), Al (ratio: 0.62), Si (ratio: 0.68), P (ratio: 0.77), K (ratio: 0.76), and Ti (ratio: 0.83) had higher loadings in the NSFB dwellings. The remaining elements, namely Cl (ratio: 27.12), Ca (ratio: 1.55), V (ratio: 42.60), Cr (ratio: 14.92), Mn (ratio: 15.26), Fe (ratio: 1.92), Cu (ratio: 1.51), Zn (ratio: 1.16), and Pb (ratio: 26.67) were higher in the ISFB dwelling during the summer compared to the NSFB.

Similar to summer, the ISFB/NSFB ratios for the winter indicated higher PM_4 concentration in the ISFB dwelling. There was a larger difference in the PM_4 loading during winter than summer. The elements that were close to unity in both the ISFB and NSFB households during winter were P, Ti, Sn, and Pb. All the remaining elements had higher loadings in the ISFB houses. The elements associated with crustal material was higher by ratios ranging between one and three. Whereas those linked to anthropogenic activities were extremely high, such as V (ratio: 20.01), Mn (ratio: 10.09), and Ba (ratio: 17.83).

The elements which were close to unity in both the ISFB and NSFB dwellings during summer and winter respectively, point toward sources that are dominant within the ambient environment, such as road traffic emission and waste burning activities. Elements associated crustal soil sources had higher mass loading in the NSFB household compared to elements of anthropogenic origin. This is supported by the crustal enrichment factor results and subsequent qualitative source apportionment results *(see Section 4.1.2.3.1 and 4.1.2.5.1)*.

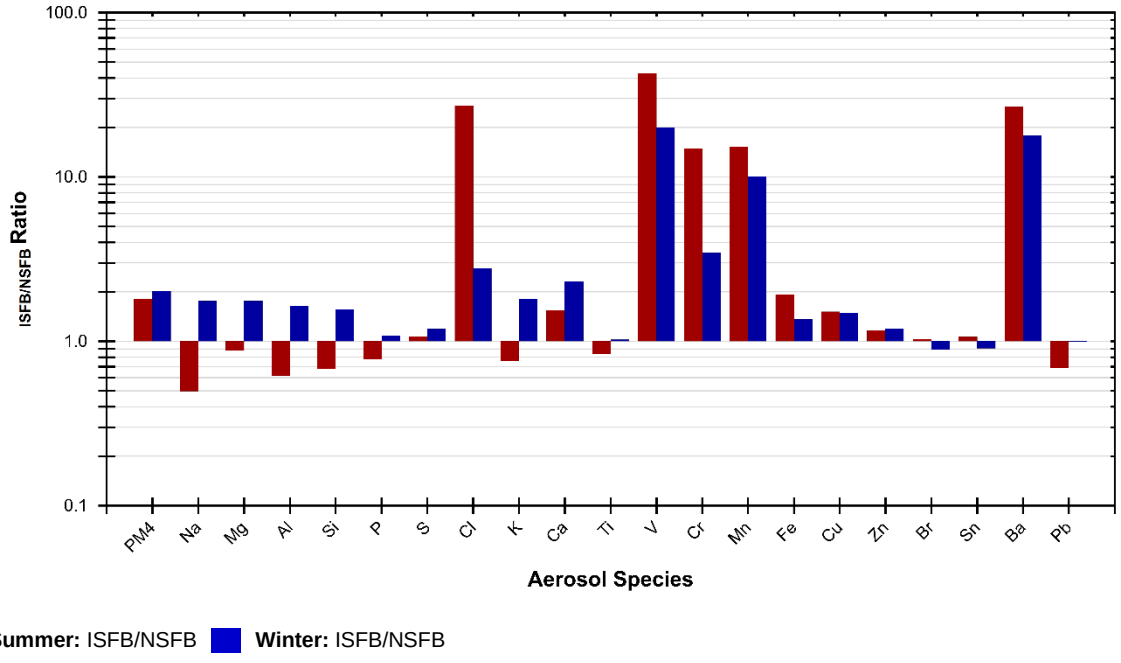

Figure 4.15 ISFB-to-NSFB household ratios of mean elemental mass concentrations of the measured PM_4 measured the residential indoor environment of coal-burning communities, categorised by season (summer and winter).

Settlement-to-settlement ratios of elemental mass concentrations within the coal-burning communities

In KwaDela (summer, ISFB dwellings), the detected elements accounted for ~38% of the measured PM_4 mass concentration *(Figure D.5.d)*. The mean detected elemental mass in KwaZamokuhle was ~31% *(Figure D.6.d)*, with the summer *(Figure D.7.d)* and winter *(Figure D.10.d)* means being ~63% and ~25%, respectively. During summer, the detected elemental mass in the ISFB- *(Figure D.8.d)* and NSFB *(Figure D.9.d)* dwellings were ~65% and ~63%. However, during winter, these values dropped to ~25% and ~32%, respectively for the ISFB- *(Figure D.11.d)* and NSFB *(Figure D.12.d)* households.

The settlement-to-settlement ratios were used to identify if there were any significant difference in the detected element mass concentrations between settlements, within the same community classification. Based on the KwaDela/KwaZamokuhle ratios, the settlement of KwaZamokuhle *(Figure D.6.d)* had higher (ratio: 0.75) mean PM_4 mass loadings than KwaDela *(Figure D.5.d)*. Three elements, namely Ti, Ba, and Pb were close to unity. KwaDela experienced higher mean concentrations of Cl (ratio: 2.75), V (ratio: 3.45), Cr (ratio: 3.77), Mn (ratio: 4.02), Fe (ratio: 1.13), Cu (ratio: 1.68), Zn (ratio: 1.14), Sn (ratio: 1.16), and Ba (ratio: 2.60). While KwaZamokuhle had higher loadings of Na (ratio: 0.18), Mg (ratio: 0.44), Al (ratio: 0.01), Si (ratio: 0.05), P (ratio: 0.21), S (ratio: 0.47), K (ratio: 0.37), and Ca (ratio: 0.66).

The high level of undetected mass, during winter, could be related to the undetected carbonaceous species. This is significant as solid fuel combustion is a major contributor to atmospheric carbon. Black carbon contributes to ~3% (summer), ~6% (winter), and ~10% (during specific peak burning times) of ambient $PM_{2.5}$ loading in KwaDela *(Xulu, 2017)*. The high variability that exists in the elemental mass concentration indicate that the individual source contributions might differ significantly bases on the settlement, season, and household fuel use classifications *(see Figure 4.37 and Figure 4.38 in Section 4.1.2.5)*.

4.1.2.2.2. Elemental mass concentrations within the urban community

The mean concentrations for the detected and discussed elements in the residential indoor environment within the urbanised community were 26.70 $\mu g.m^{-3}$, which was ~36% of the mean PM_4 loading *(Table 4.4* and *Figure D.13.d)*. The most abundant detected element, accounting for between 5 to <10% of PM_4, was Si. The second most abundant element, accounting between 3 and <5% of the PM_4, was Na. The third group of elements, each contributing between 1 and <3% to the PM_4, included Mg, Al, S, Cl, K, Ca, Fe, Cu, Zn, Sn, Ba, and Pb. The fourth group of elements, each contributing between 0.1 and 1% to the PM_4 loading, included Ti, V, Cr, and Mn. The least prominent elements were P and Br, contributing <0.1% of the total PM_4 mass.

Season-to-season ratios of elemental mass concentrations within the urban community

The summer-to-winter PM_4 and elemental mass concentration ratios are presented in *(Figure 4.16)*. The mean PM_4 loading is similar (ratio: 1.00) during both seasons in the urban community of Jouberton. The mean summer concentrations for the analysed elements was 28.45 $\mu g.m^{-3}$, which was ~38% of the mean PM_4 loading *(Figure D.14.d)*. The winter mean for the analysed elements was similar and at 24.13 $\mu g.m^{-3}$, however, it only accounted for ~32% of the mean collected PM_4 mass *(Figure D.17.d)*. The ratios indicated that a number of the elements (Al, P, K, Zn, and Sn) were close to unity, thus having similar loading during both summer and winter. Other elements such as Mg (ratio: 0.82), Si (ratio: 0.82), Fe (ratio: 0.70), and Br (ratio: 0.73) experienced higher mass loadings during summer. Majority of the elements (Na, S, Cl, Ca, Ti, V, Cr, Mn, Cu, Ba, and Pb) had higher mass loadings during the winter. The summer-to-winter ratios for the ISFB and NSFB households showed a similar trend as the overall summer-to-winter comparison *(Figure 4.16)*. The only significant differences were that the PM_4 mass concentration was higher (ratio: 0.57) in the NSFB dwelling during winter compared to summer and similarly K (ratio: 0.67) also had higher concentrations. The ISFB dwellings showed a higher seasonal variability in their elemental concentrations compared to the NSFB houses for elements associated with anthropogenic activities. There is much less variation for crustal soil elements. Re-suspended crustal material is a consistent source of atmospheric PM loading. The higher K concentrations is associated with some level of biomass burning activities identified through the EFs and qualitative source apportionment *(see Sections 4.1.2.3.2 and 4.1.2.5.2)*.

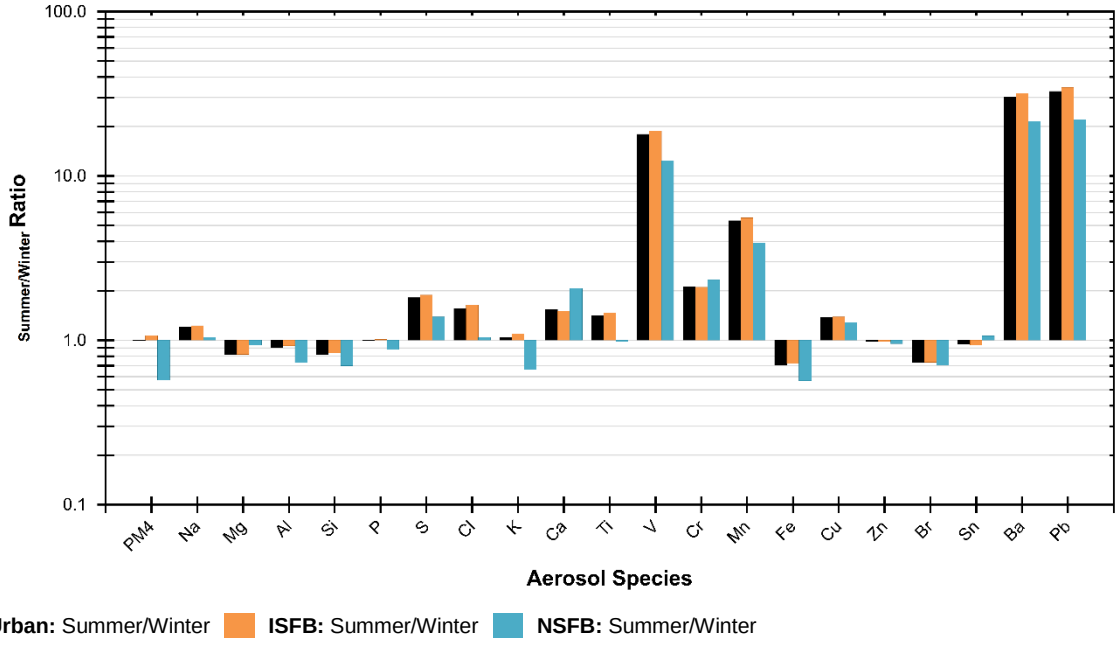

Figure 4.16 Summer-to-winter ratios of mean elemental mass concentrations of the measured PM_4 measured the residential indoor environment of urbanised-burning communities, categorised by ISFB- and NSFB households.

Household-to-household ratios of elemental mass concentrations within the urban community

During summer, the detected elemental mass in Jouberton in the ISFB- *(Figure D.15.d)* and NSFB *(Figure D.16.d)* dwellings were ~44% and ~37%. However, during winter, these values dropped to ~24% and ~33%, respectively for the ISFB- *(Figure D.18.d)* and NSFB *(Figure D.19.d)* households. The seasonal household-to-household ratios are shown in *Figure 4.17*.

The ISFB/NSFB ratios for the summer indicated that the ISFB has a higher PM_4 loading compared to the NSFB dwellings. Some elements (P, Ca, Cu, Zn, and Sn) were close to unity indicating that these elements had similar mass loadings in both the ISFB and NSFB households during summer. The remaining element ratios were >1, indicating higher loadings in the ISFB households during summer, compared to the NSFB dwellings. The winter ISFB/NSFB ratios were more complex. The NSFB households had higher PM_4 levels (ratio: 0.75) than the ISFB. Ten of the elements (Al, Si, P, Ti, Mn, Fe, Cu, Zn, Br, and Sn) were close to unity during winter. Elements that had higher concentrations within the ISFB dwelling included Na (ratio: 1.11), Mg (ratio: 1.55), Ca (ratio: 1.50), and Cr (ratio: 1.38). While S (ratio: 0.82), Cl (ratio: 0.72), K (ratio: 0.74), V (ratio: 0.83), Ba (ratio: 0.81), and Pb (ratio: 0.76) concentrations were higher in the NSFB houses during winter.

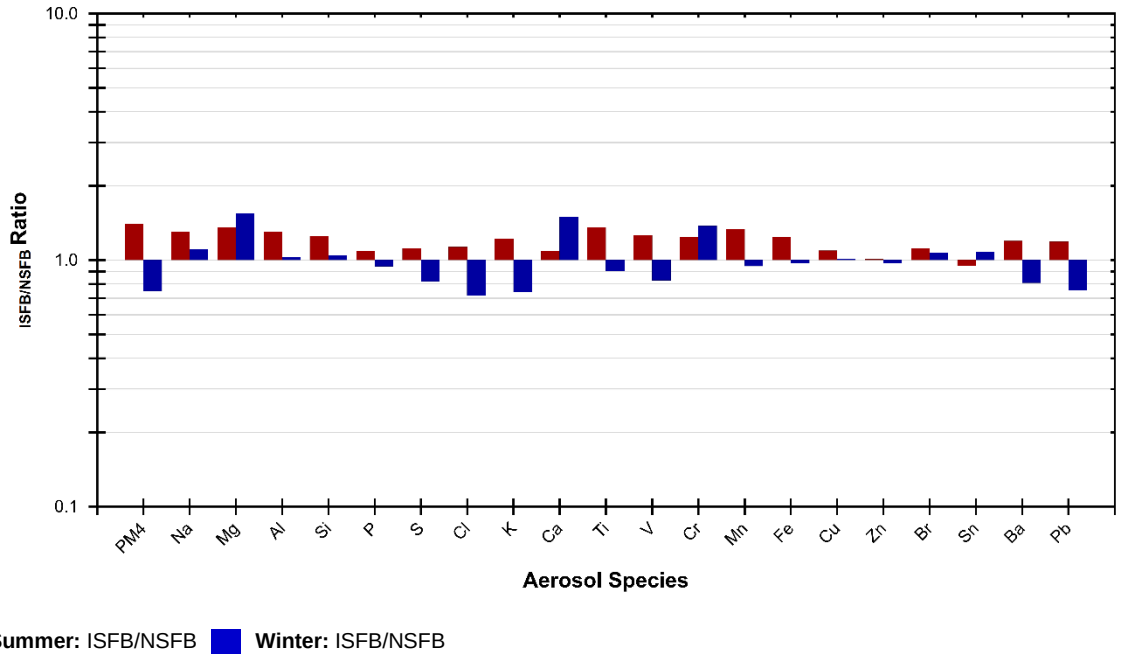

Figure 4.17 ISFB-to-NSFB household ratios of mean elemental mass concentrations of the measured PM_4 measured the residential indoor environment of urbanised community, categorised by season (summer and winter).

The elements that were close to unity in both the ISFB and NSFB houses, during both summer and winter, most probably originated from a mutual source found within the ambient environment. During summer,

this source is most likely to be waste burning (indicated by the Sn enrichment), while for winter it is a combination of crustal soil (Al and Si), road traffic (Zn), and waste burning (Sn) *(see Figure 4.37 and Figure 4.38 in Section 4.1.2.5)*. The smaller difference in the elemental mass concentration between the ISFB and NSFB dwellings, within the individual seasons, indicates that the various source contributions are similar.

4.1.2.2.3. Elemental mass concentrations within the wood burning community

The mean concentrations for the detected and discussed elements in the residential indoor environment within the wood-burning communities were 35.27 µg.m^{-3}, which was ~44% of the mean PM_4 loading *(Table 4.4* and *Figure D.20.d)*. The most abundant detected elements, each accounting for between 5 to <10% of PM_4, was Na and Si. The second group of most abundant elements, each accounting between 1 and <3% of the PM_4, was Mg, Al, S, Cl, K, Ca, Fe, Cu, Zn, Sn, Ba, and Pb. The third group of elements, each contributing between 0.1 and <1% to the PM_4, included Ti, V, Cr, and Mn. The least prominent elements were P and Br, contributing <0.1% of the total PM_4 mass.

Season-to-season ratios of elemental mass concentrations within the wood-burning communities

The summer-to-winter PM_4 and elemental mass concentration ratios are presented in *(Figure 4.18)*. The mean PM_4 loading is similar (ratio: 0.93) during both summer and winter. The mean summer concentrations for the analysed elements was 23.35 µg.m^{-3}, which was ~30% of the mean PM_4 loading *(Figure D.21.d)*. The winter mean for the analysed elements was similar and at 46.41 µg.m^{-3}, however, it only accounted for ~56% of the mean collected PM_4 mass *(Figure D.22.d)*. The summer-to-winter rations indicated that Zn, Br, and Sn are close to unity, thus indicating similar mass loadings during both summer and winter. All the remaining elements showed increased mass loadings during the winter.

The elements that were close to unity (Zn, Br, and Sn) had similar mass concentrations, each accounting between 0.1 and 3% of the measured PM_4. This indicates that there is at least one constant ambient source contributing to these elements during both summer and winter.

The summer-to-winter ratios for the ISFB, NSFB, and OSFB households showed a similar trend as the overall summer-to-winter comparison *(Figure 4.18)*. The only noticeable difference is that the ISFB dwellings showed slightly increased concentrations of Br (ratio: 1.14) during the winter compared to summer.

The households showed very little seasonal variability in the PM_4 element mass concentrations, indicating that these houses have similar sources contributing to the indoor PM_4 during both summer and winter. The NSFB households had increased seasonal variability associated with the detected element mass concentrations. The increased mass concentrations of Ba and Br within the wood-burning communities is

significant as these two elements are known tracers for both road biomass- and waste burning related activities. To a lesser degree it is associated with rad traffic emissions.

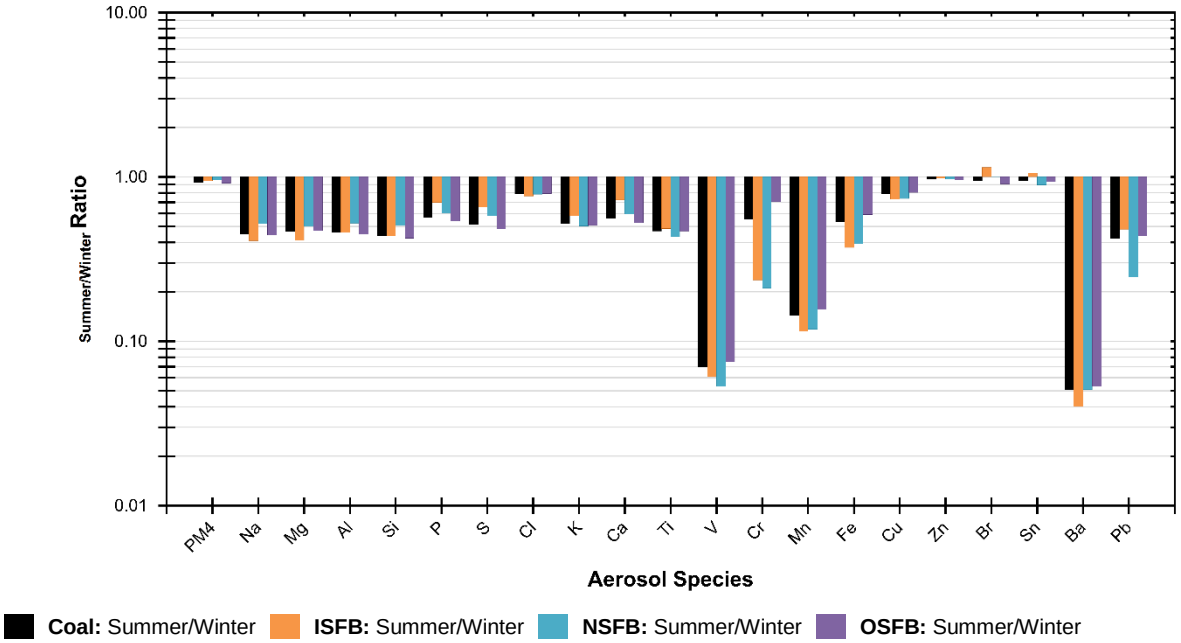

Figure 4.18 Summer-to-winter ratios of mean elemental mass concentrations of the measured PM_4 measured the residential indoor environment of urbanised-burning communities, categorised by ISFB-, NSFB- and OSFB households.

Household-to-household ratios of elemental mass concentrations within the wood-burning communities

The seasonal household-to-household ratios are shown in *Figure 4.19*, *Figure 4.20* and *Figure 4.21*. The ISFB/NSFB ratios *(Figure 4.19)* for the summer indicated that the ISFB has a higher PM_4 loading compared to the NSFB dwellings. Some elements (Al, Si, Cl, V, Mn, Cu, Zn, Br, and Ba) were close to unity indicating that these elements had similar mean loadings in both the ISFB and NSFB households during summer. Na (ratio: 0.86) and Mg (ratio: 0.85) had higher summer loadings in the NSFB dwellings, while P (ratio: 1.17), S (ratio: 1.30), K (ratio: 1.14), Ca (ratio: 1.62), Ti (ratio: 1.19), Cr (ratio: 1.40), Fe (ratio: 1.11), Sn (ratio: 1.10), and Pb (ratio: 1.68) experienced higher mass concentrations in the ISFB households. Similar to summer, the ISFB/NSFB ratios for the winter *(Figure 4.19)* indicated higher PM_4 concentration in the ISFB dwelling. Majority of the elements (Na, Mg, Al, Si, P, S, Cl, Ti, V, Mn, Cu, Zn, and Sn) in the ISFB and NSFB households were close to unity. The Ca (ratio: 1.32), Cr (ratio: 1.25), Fe (ratio: 1.17), and Ba (ratio: Ba) elements had higher loadings in the ISFB dwellings during winter, while Br (ratio: 0.85) and Pb (ratio: 0.86) were higher in the NSFB houses.

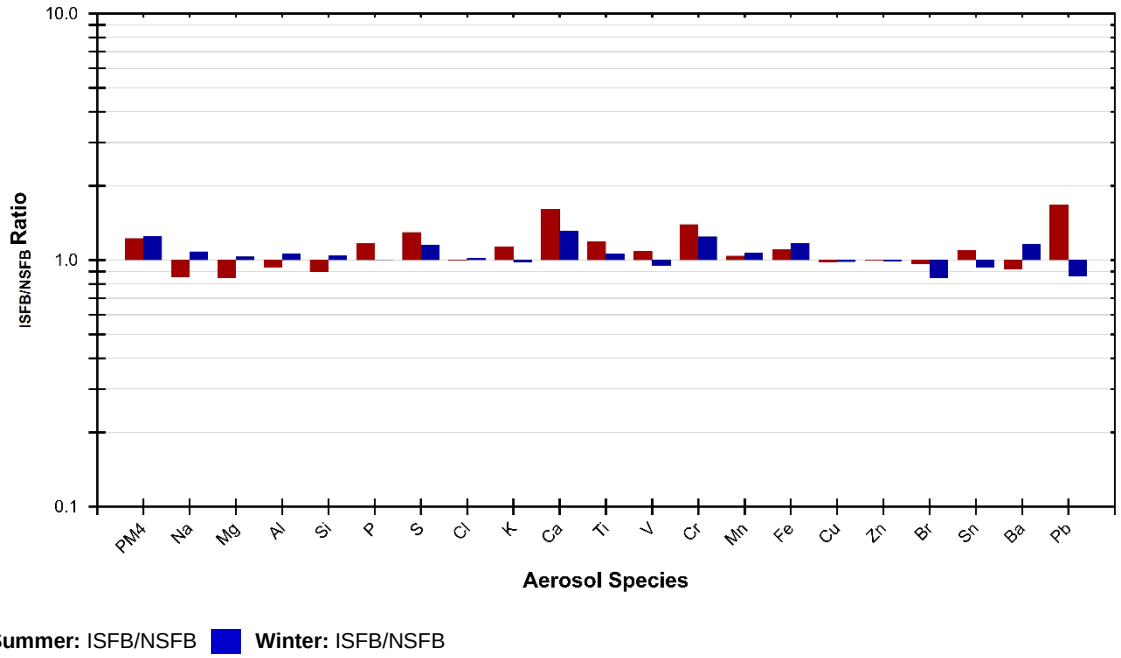

Figure 4.19 ISFB-to-NSFB household ratios of mean elemental mass concentrations of the measured PM_4 measured the residential indoor environment of wood-burning communities, categorised by season (summer and winter).

The ISFB/OSFB ratios *(Figure 4.20)* for the summer and winter indicated higher PM_4 loadings in the ISFB houses compared to the OSFB. The elements that were close to unity included Na, Mg, Cl, V, Mn, Cu, Zn, and Sn. During summer, Al (ratio: 1.12), Si (ratio: 1.11), P (ratio: 1.28), S (ratio: 1.34), K (ratio: 1.20), Ca (ratio: 1.53), Ti (ratio: 1.23), Br (ratio: 1.11), and Pb (ratio: 1.22) had higher loadings in the ISFB- than the OSFB dwellings. The few remaining elements (Cr, Fe, and Ba) experienced higher summer mass loadings in OSFB households. During winter, Mg (ratio: 1.17), Al (ratio: 1.10), Ca (ratio: 1.10), Ti (ratio: 1.18), V (ratio: 1.33), Cr (ratio: 1.51), Mn (ratio: 1.46), Fe (ratio: 1.23), Ba (ratio: 1.16), and Pb (ratio: 1.12) had higher mass concentration loadings in the ISFB dwellings compared to the OSFB. The only element that showed prominence in the OSFB houses during winter was Br (ratio: 0.88). The remaining elements (Na, Si, O, S, Cl, K, Cu, Zn, and Sn) were close to unity in both the ISFB and OSFB households during winter.

The NSFB/OSFB ratios *(Figure 4.21)* for the summer indicated that there was little variation between the NSFB and OSFB dwellings, except for a specific few elements. In the NSFB dwelling, Na (ratio: 1.10), Mg (ratio: 1.21), Al (ratio: 1.20), Si (ratio: 1.23), P (ratio: 1.10) and Zn (ratio: 1.15) had higher summer loadings. Three elements, namely Cr (ratio: 0.36), Fe (ratio: 0.70), and Pb (ratio: 0.73) experienced higher mass loadings in the OSFB during summer. During winter, the elements that had higher mass loadings in the NSFB dwellings included Mg (ratio: 1.14), Ti (ratio: 1.11), V (ratio: 1.40), Cr (ratio: 1.21), Mn (ratio: 1.36), Cu (ratio: 1.11), and Pb (ratio: 1.30). There were two elements, namely S (ratio: 0.85) and Ca (ratio: 0.84) that were prominent in the OSFB households during winter.

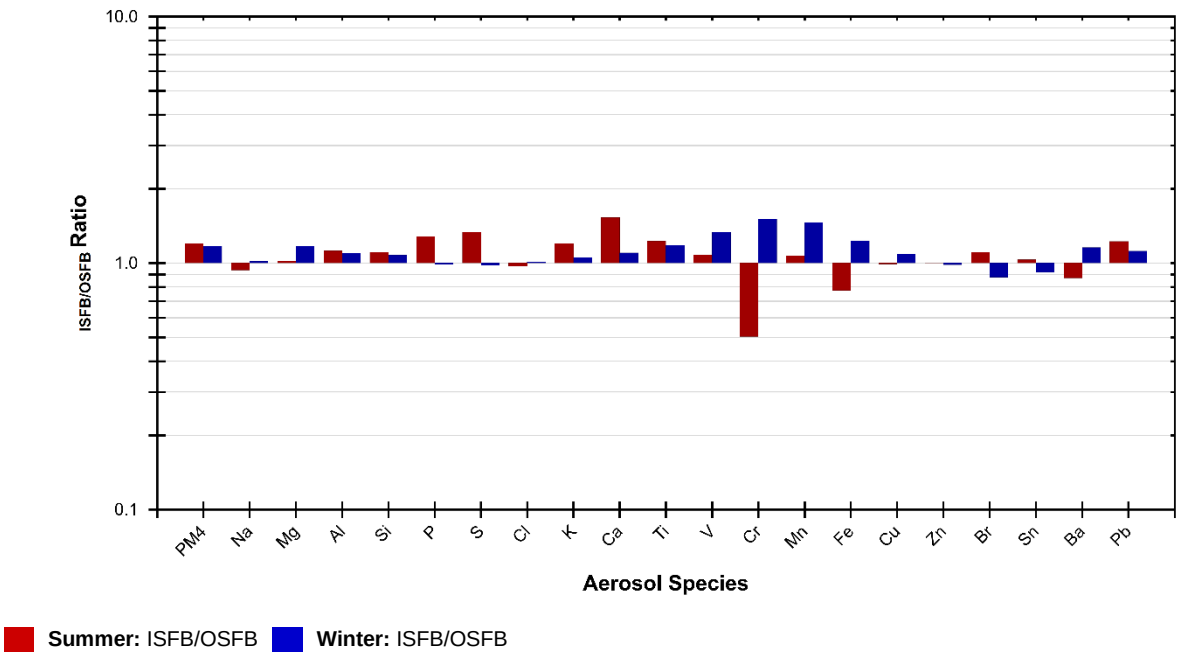

Figure 4.20 ISFB-to-OSFB household ratios of mean elemental mass concentrations of the measured PM_4 measured the residential indoor environment of wood-burning communities, categorised by season (summer and winter).

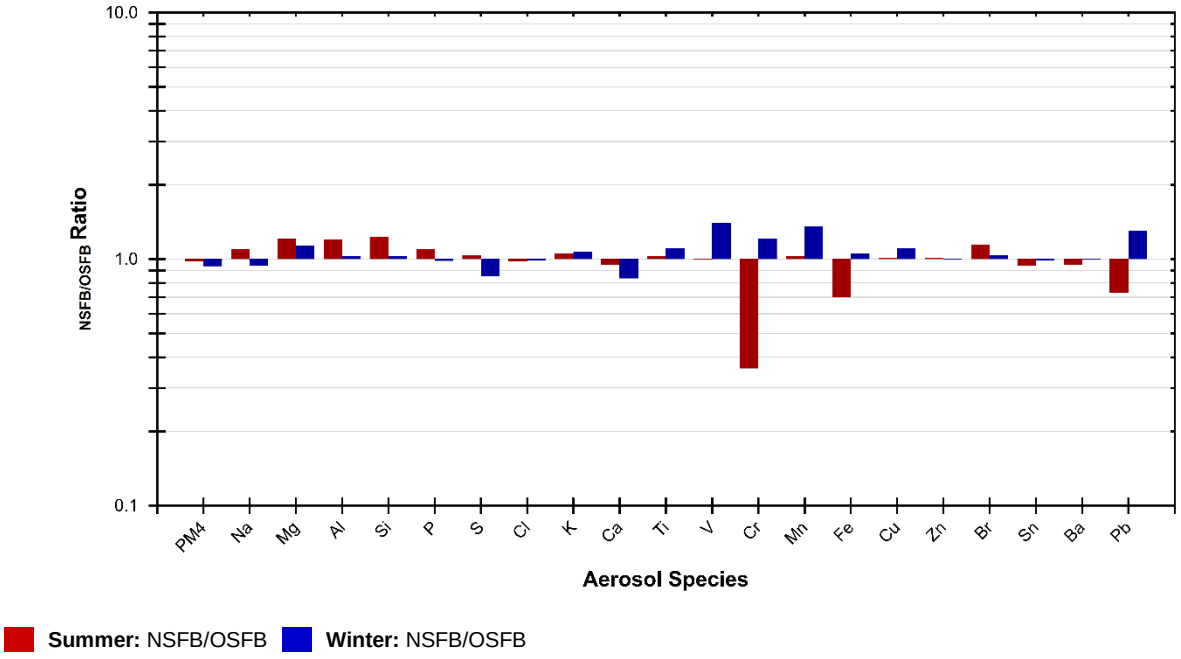

Figure 4.21 NSFB-to-OSFB household ratios of mean elemental mass concentrations of the measured PM_4 measured the residential indoor environment of wood-burning communities, categorised by season (summer and winter).

Settlement-to-settlement ratios of elemental mass concentrations within the wood-burning communities

In Agincourt, the mean detected elemental mass was ~44% *(Figure D.23.d)*, with the summer *(Figure D.24.d)* and winter *(Figure D.28.d)* means being ~31% and ~54%, respectively. During summer, the detected elemental mass in the ISFB- *(Figure D.25.d)*, NSFB- *(Figure D.26.d)*, and OSFB *(Figure D.27.d)* dwellings were ~27%, ~34% and ~32%. However, during winter, these values increased to ~51%, ~58%, and ~54%, respectively for the ISFB- *(Figure D.29.d)*, NSFB- *(Figure D.30.d)*, and OSFB *(Figure D.31.d)* households.

The mean detected elemental mass in Giyani was ~39% *(Figure D.32.d)* with the spring, summer *(Figure D.33.d)* and winter *(Figure D.36.d)* means being ~33%, ~21%, and ~78%, respectively. During spring, the detected elemental mass in the ISFB-, NSFB-, and OSFB houses were ~26%, ~41%, and ~34%. In summer, the detected elemental mass in the NSFB- *(Figure D.34.d)* and OSFB *(Figure D.35.d)* dwellings were ~24% and ~18%. Thus, it was similar to spring for the NSFB, however, for the OSFB it was a factor of four lower. However, during winter, these values increased to ~100% and ~77%, respectively for the ISFB- *(Figure D.37.d)* and NSFB *(Figure D.38.d)* households.

The settlement-to-settlement ratios were used to identify if there were any significant difference between settlements within the same community classification. Based on the Agincourt/Giyani ratios, the settlement had similar (ratio: 0.92) mean PM_4 mass loading *(Figure D.23.d and Figure D.32.d)*. Four elements, namely Mg, S, K, and Zn were close to unity for these two settlements. The majority of the elements had a higher mean mass loading in Agincourt. These included Na (ratio: 1.70), Al (ratio: 1.26), Si (ratio: 1.34), Cl (ratio: 1.24), Ca (ratio: 1.21), V (ratio: 8.11), Mn (ratio: 3.74), Cu (ratio: 1.11), Br (ratio: 1.37), and Ba (ratio: 11.70). A few of the elements showed higher mean mass concentration in Giyani, namely P (ratio: 0.76), Ti (ratio: 0.61), Cr (ratio: 0.35), Fe (ratio: 0.40), Sn (ratio: 0.87), and Pb (ratio: 0.40).

Similar to the urban community, there is small variability between the ISFB, NSFB, and OSF households. The sources are thus expected to contribute similarly within the various households, during summer and winter *(see Figure 4.37 and Figure 4.38 in Section 4.1.2.5)*.

The variations in the elemental abundance found within the residential indoor environment were investigated based on the community, settlement, season and household fuel use classification. The crustal enrichment of these elements is discussed in further detail in the following section.

4.1.2.3. Crustal enrichment factors (EFs) of indoor PM4 elemental mass concentrations

In order to assess the effect of anthropogenic activities on the respirable particulate loading within the residential indoor environment, and also measure the extent of crustal and non-crustal contributions to the

elemental concentrations levels, the enrichment factors (EFs) were calculated according to *Equation 2.18 (see Chapter 2, Section 2.4.3.2.4)*.

EF values close to unity (=1) indicates that crustal soil was the main source contributing to the specific element. EF ranging between one (>1) and five (≥5) have a low level of enrichment indicating that the elements result in some small part from crustal material that has a different mineral composition or contribution from other sources besides the crustal soil material. The EFs more than five (>5) show a moderate enrichment and suggests that anthropogenic emissions were a dominant contributing source to the specific elements. Finally, the EFs that are above ten (≥10) are highly enriched and point toward a significant fraction of the elements being of a non-crustal origin *(Gholampour et al., 2016)*. The elements with EFs >1000 are extremely enriched.

The estimated mean EFs of the measured PM_4 trace elements, within the residential indoor environment (calculated as an average of all samples) of various low-income settlements in South Africa, are given in *Figure 4.22 (also see Figure D.1.c)*.

It can be observed that the EFs for Si was between 1 and 5 (low enrichment); so, it can be concluded that the major fraction of this element originates from the resuspension of crustal soil material. There were a number of elements (Mg, P, and K) that showed moderate enrichment with EF ranging between 5 and 10. High EFs (>10-1000) were observed for Na, S, Ca, Ti, Mn, and Fe while extreme EF (>1000) were detected for Cl, V, Cr, Cu, Zn, Br, Sn, Ba, and Pb. This could indicate that for these specific elements originate from sources other than crustal soil materials.

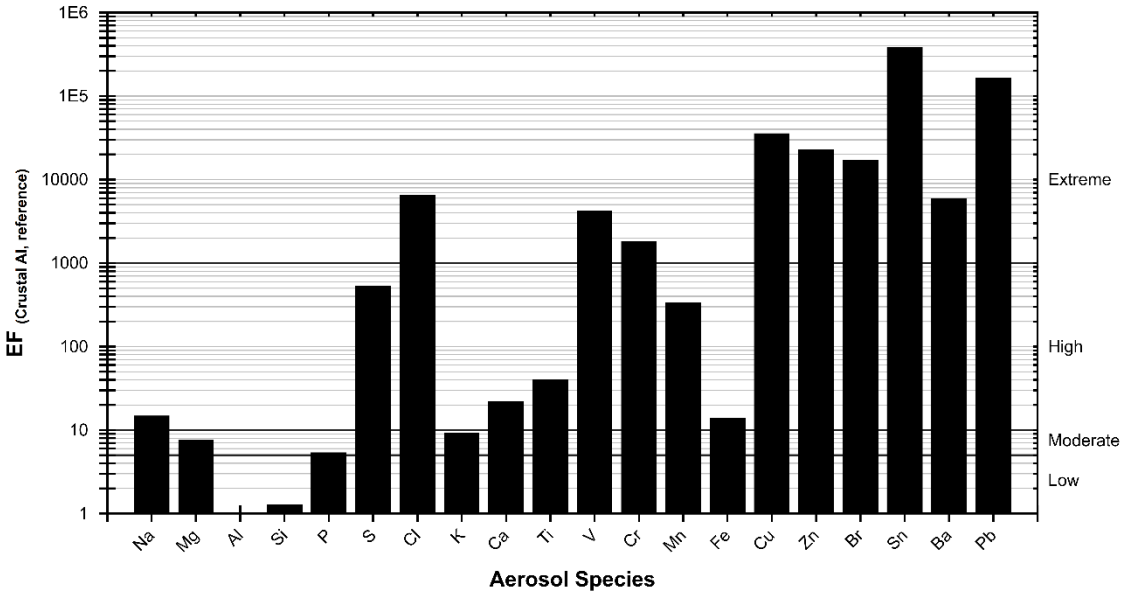

Figure 4.22 Crustal enrichment factors (EFs) of the measured PM_4 inorganic trace elements within the residential indoor environment of low-income settlement in South Africa. (*Reference:* Crustal Al)

Community-to-community ratios of the crustal EFs

The community-to-community ratios of the mean EFs are used to evaluate whether there are obvious differences in the origin (natural or anthropogenic) of the trace elements measured within the coal-burning- (Coal), urbanised- (Urban), and wood-burning (Wood) communities *(Figure 4.23)*. Ratios that were >0.90 and <1.10 were considered close to unity.

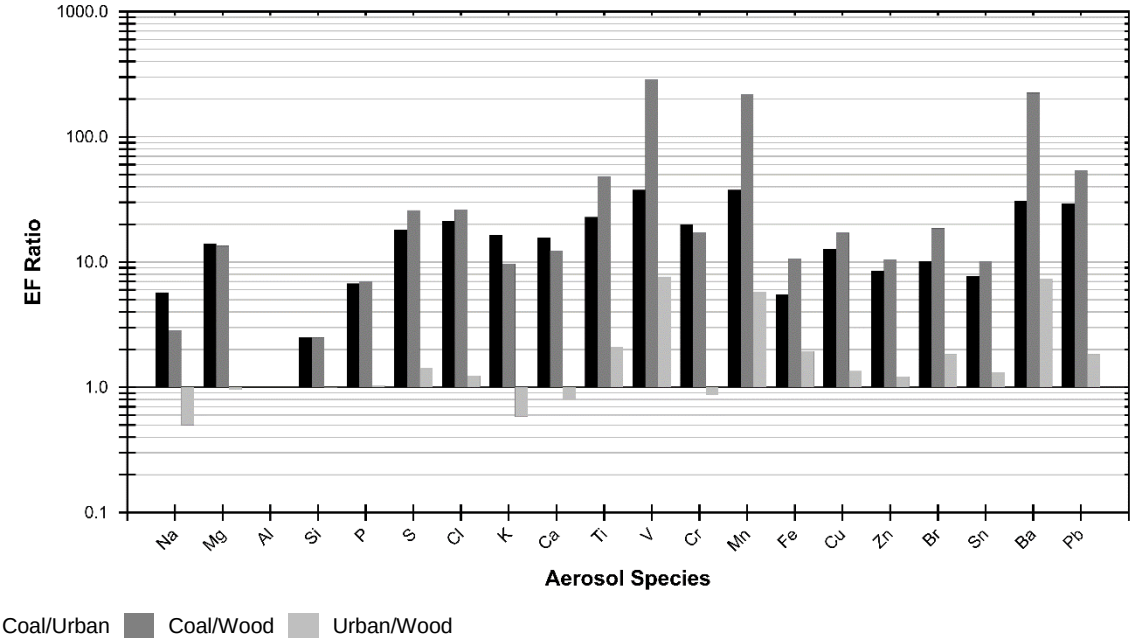

Figure 4.23 Community ratios of mean crustal enrichment factors (EFs) of the measured PM_4 trace elements.

The Coal/Urban community EF ratios indicate that the coal-burning community experienced higher levels of enrichment for all elements. Si, which had a low enrichment, was higher by a factor (or ratio) of 2.50. The highly enriched elements of Na, Mg, P, K, Ca, Ti, and Fe was higher by factors ranging between 5.50 (Fe) and 22.89 (Ti). While the extremely enriched elements of S, Cl, V, Cr, Mn, Cu, Zn, Br, Sn, Ba and Pb showed higher levels of enrichment ranging between 7.68 (Sn) to 37.59 (V).

The Coal/Wood community EF ratios had a similar profile to that of the Coal/Urban as the coal-burning community had higher levels of element enrichment, compared to the wood-burning communities. The difference (ratio: 2.49) in the Si enrichment was almost exactly the same as the Coal/Urban. A few of the elements, namely, Na, K, Ca, and Cr had a slightly lower ratio, thus having a smaller difference in its enrichment within the two communities. The remaining elements (S, Cl, Ti, V, Mn, Fe, Cu, Zn, Br, Sn, Ba, and Pb) showed an increased difference in its enrichment level.

The Urban/Wood Community EF ratios were very different from those observed for the Coal/Urban and Coal/Wood comparisons. Mg, Si, and P enrichment were close to unity. The majority of the elements showed increased levels of enrichment, with ratios ranging between 1.22 (Zn) to 7.64 (V), in the urbanised

community, with the exception of Na and K. The latter had higher levels of enrichment in the wood-burning communities. This is not surprising as these are traces for biomass combustion.

Thus, the urban- and wood-burning communities showed similarities in the mean levels of enrichment, whereas the coal-burning communities experienced much higher levels of enrichment. This indicates that anthropogenic sources could contribute significantly to the indoor PM_4 loadings within the coal-burning communities.

Similar to the difference observed in the elemental mass concentrations, due to the spatial distribution of the settlements, the associated crustal enrichment is also expected to vary. Due to the differences observed between the mean community-to-community EF ratios, the EFs were further investigated based on the community, settlement, season, and household fuel use categorisation *(Table 4.5)*. These results are investigated further in the following Sections *4.1.2.3.1*, *4.1.2.3.2*, and *0*.

4.1.2.3.1. Crustal EFs within the coal-burning communities

The EFs in the coal-burning communities *(Table 4.5 and Figure D.2.c)* showed low enrichment of Si. The P, Mg, Na, K, Fe, Ca, and Ti elements were highly enriched while Mn, S, Cr, V, Ba, Cl, Br, Zn, Cu, Pb, and Sn showed extreme enrichment.

Season-to-season ratios of the crustal EFs within the coal-burning communities

The summer-to-winter ratios of the enrichment factors for elements measured within the coal-burning communities are given in *Figure 4.24* (elements were ranked by level of enrichment from low to extreme). The summer element mass concentrations showed similar levels of enrichment *(Figure D.3.c)* as the overall mean for the coal-burning community. The winter enrichment *(Figure D.4.c)* varied from that observed during summer. Low levels of enrichment were seen for Si and Mg, while Fe and P were moderately enriched. The Na, Ti, K, Ca, Mn, Cr, V, and S elements were highly enriched while Ba, Cl, Zn, Cu, Br, Pb, and Sn showed extreme enrichment.

All the elements showed higher levels of enrichment during the summer. The Si, Br, K, P, S, Na, and Zn elements had enrichment level that was higher by factors (or ratios) ranging between 3.62 (Si) to 7.03 (Zn). Ca, Cu, Sn, Cl, and Fe enrichments were higher by ratios ranging between 11.19 (Ca) and 18.48 (Fe). The remaining elements (Mg, Ti, Cr, Pb, Ba, Mn, and V) had ratios above 20.

Table 4.5 Average enrichment factors (crustal Al as reference) of the elements found within the residential indoor PM_4 loadings categorised by community, settlement, season and household solid fuel use. Presented in order from lowest to highest level of enrichment.

Settlement	Season	Fuel Use	Enrichment Factor			
			Low (< 5)	**Moderate (≤ 5 to <10)**	**High (≤ 10 to <1000)**	**Extreme (≥ 1000)**
Coal-burning Communities						
KwaDela	Summer	ISFB		Si	P, Mg, Na, K, Fe, Ca, Ti	Mn, S, Cr, Ba, V, Cl, Br, Zn, Cu, Pb, Sn
KwaZamokuhle	Summer	ISFB	Si, Fe, Mg, K, Na, P, Ca, Mn	Ti	V, Cr, Ba, Cl, S	Br, Zn, Cu, Pb, Sn
		NSFB	Si, Fe, P, Mg, K, Na	Ca	Mn, V, Ti, Cr, Ba, Cl, S	Br, Zn, Cu, Sn, Pb
	Winter	ISFB	Si, Mg	Fe, P	Na, Ti, K, Ca, Mn, Cr	V, S, Ba, Cl, Zn, Cu, Pb, Br, Sn
		NSFB	Si, Mg, Fe, P, K	Na, Mn, Ca	Ti, V, Cr, Ba, S, Cl	Br, Zn, Cu, Pb, Sn
Summer			Si	-	P, Mg, Na, K, Fe, Ca, Ti	Mn, S, Cr, Ba, V, Cl, Br, Zn, Cu, Pb, Sn
Winter			Si, Mg	Fe, P	Na, Ti, K, Ca, Mn, Cr, V, S	Ba, Cl, Zn, Cu, Br, Pb, Sn
Coal-burning Community			Si	-	P, Mg, Na, K, Fe, Ca, Ti	Mn, S, Cr, V, Ba, Cl, Br, Zn, Cu, Pb, Sn
Urbanised Community						
Jouberton	Summer	ISFB	Si, Mg, Fe, K, P, Ti	Ca, Na	Mn, Cr, S, V, Ba, Cl	Br, Zn, Cu, Pb, Sn
		NSFB	Si, P, Mg, K, Fe	Na, Ca	Ti, Mn, S, Cr	V, Ba, Cl, Zn, Br, Cu, Pb, Sn
	Winter	ISFB	Si Mg, K, P, Ti, Fe	Mn, Na, Ca	Ba, V, S, Cr, Pb	Cl, Br, Zn, Cu, Sn
		NSFB	Si, Mg, K, P	Ca, Na	Ti, Fe, Mn, Ba, V, S, Cr	Cl, Pb, Br, Zn, Cu, Sn
Summer			Si, P, Mg, K, Fe	Na, Ca	Ti, Mn, S, Cr	V, Ba, Cl, Zn, Br, Cu, Pb, Sn
Winter			Si, Mg, K, P	Ca, Na	Ti, Fe, Mn, Ba, V, S, Cr	Cl, Pb, Br, Zn, Cu, Sn
Urban Community			Si, Mg, K, P	Na, Ca	Fe, Ti, Mn, S, Cr, V, Ba	Cl, Br, Zn, Cu, Pb, Sn

Table 4.5 (Continues)

Settlement	Season	Fuel Use	Enrichment Factor			
			Low (< 5)	**Moderate (≤ 5 to <10)**	**High (≤ 10 to <1000)**	**Extreme (≥ 1000)**
Wood-burning Communities						
Agincourt	Summer	ISFB	Si, Mg, P, Fe, K	Ti, Mn	Na, Ca, V, Ba, S, Cr	Cl, Br, Zn, Cu, Pb, Sn
		NSFB	Si, Fe, Ti, Mg, P, K	Ca	Mn, Na, V, S, Cr, Ba	Cl, Pb, Br, Zn, Cu, Sn
		OSFB	Si, Mg, P	Fe, K, Ti	Ca, Mn, Na, V, Ba, S, Cr	Cl, Br, Zn, Cu, Pb, Sn
	Winter	ISFB	Si, P, Mg, Ti, Fe, K	Ca, Mn	Na, S, Ba, V, Cr, Cl	Br, Pb, Zn, Cu, Sn
		NSFB	Si, Fe, P, K, Ti, Mg, Ca	-	Na, Mn, S, V, Cr, Ba, Cl	Br, Zn, Cu, Pb, Sn
		OSFB	Si, P, Ti, Fe, Mg, K	Ca, Mn	, Na, V, S, Ba, Cr, Cl	Br, Pb, Zn, Cu, Sn
Giyani	Spring	ISFB	Si, Mn, Fe, V, Ca, P, Ti, K	Mg, Na	Cr, S, Cl, Br, Zn, Cu	Pb, Sn
		NSFB	Si, Fe, Mn, Ca, Ti, P, K, V	Na, Mg	Cr, S, Cl, Br, Zn, Cu	Pb, Sn
		OSFB	Si, Fe, Mn, Ca, Ti, K, P, Na, V	Mg	Cr, S, Cl, Zn, Br, Cu	Pb, Sn
	Summer	NSFB	Si, Fe, P, K	Ca, Mn, Ti, Mg	V, Ba, Na, Cr, S	Cl, Br, Zn, Cu, Pb, Sn
		OSFB	Si	P, Mn, Mg, K, Ca	Ti, Na, Fe, Ba, V, S	Cl, Br, Zn, Cr, Cu, Pb, Sn
	Winter	NSFB	Si, Fe, Mn, P	K, Mg, Na	Ti, Ca, Ba, V, S, Cr, Cl	Zn, Cu, Br, Pb, Sn
		OSFB	Fe, Si, Mn, P, K, Ca, Ti, Mg	Ba, V, Na	Cr, S, Cl, Br, Zn, Cu	Pb, Sn
Spring			Si, Fe, Mn, Ca, Ti, P, K, V	Na, Mg	Cr, S, Cl, Br, Zn, Cu	Pb, Sn
Summer			Si, Mg, P	K, Fe, Ti	Ca, Mn, Na, V, Ba, S, Cr	Cl, Br, Zn, Cu, Pb, Sn
Winter			Si, P, Fe, Ti, Mg, K	Ca, Mn	Na, S, V, Ba, Cr, Cl	Br, Zn, Cu, Pb, Sn
Wood-burning Communities			Si, Mg, P, K	Fe, Ti, Ca	Mn, Na, V, S, Ba, Cr	Cl, Br, Zn, Cu, Pb, Sn
Residential Indoor			Si	P, Mg, K	Fe, Na, Ca, Ti, Mn, S	Cr, V, Ba, Cl, Br, Zn, Cu, Pb, Sn

The summer-to-winter ratios for the ISFB households showed a similar trend as the overall summer-to-winter comparison *(Figure 4.24)*. However, the summer-to-winter ratios for the NSFB households were slightly different as majority of the elements showed higher levels of enrichment during the winter (ratios <1), with the exception of Mg (ratio: 1.14), Mn (ratio: 1.70), and Pb (ratio: 1.22). The elements that had higher mass concentrations in the NSFB dwellings during winter tended to have higher levels of enrichment, such Cl (ratio: 0.11) and Cr (ratio: 0.22).

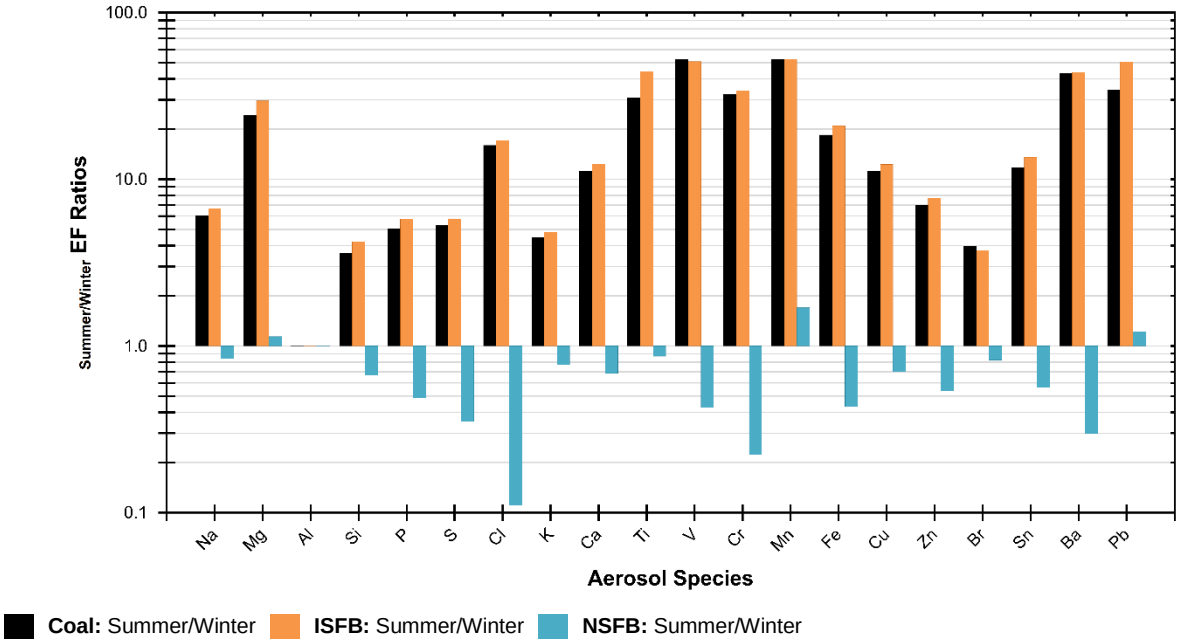

Figure 4.24 Summer-to-winter ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of coal-burning communities, categorised by ISFB- and NSFB households.

This indicates the indoor PM_4 elements experiences similar levels of enrichment in the ISFB households during both summer and winter. This points towards similar sources contributing to the mass loadings of these elements in the ISFB. However, the higher level of enrichment experienced in the NSFB households during winter, indicates higher contribution of anthropogenic sources compared to summer.

Household-to-household ratios of the crustal EFs within the coal-burning communities

The household-to-household ratios of the element enrichment factors categorised by season are given in *Figure 4.25*. The ISFB/NSFB ratios for the summer indicated that all the elements had higher levels of enrichment within the ISFB dwellings compared to the NSFB. The ratios ranged between 7.50 (Si) and 2792.45 (V). During winter, the ISFB/NSFB ratios showed less variation between the two types of households. The ISFB dwellings still had higher levels of enrichment for the majority of the elements (ranging between 1.19 (Si) and 23.48 (V)), with the exception of Ti (ratio: 0.49) and Pb (ratio: 0.47), which had higher EFs in the NSFB houses. Mg was close to unity during the winter for the ISFB/NSFB comparison.

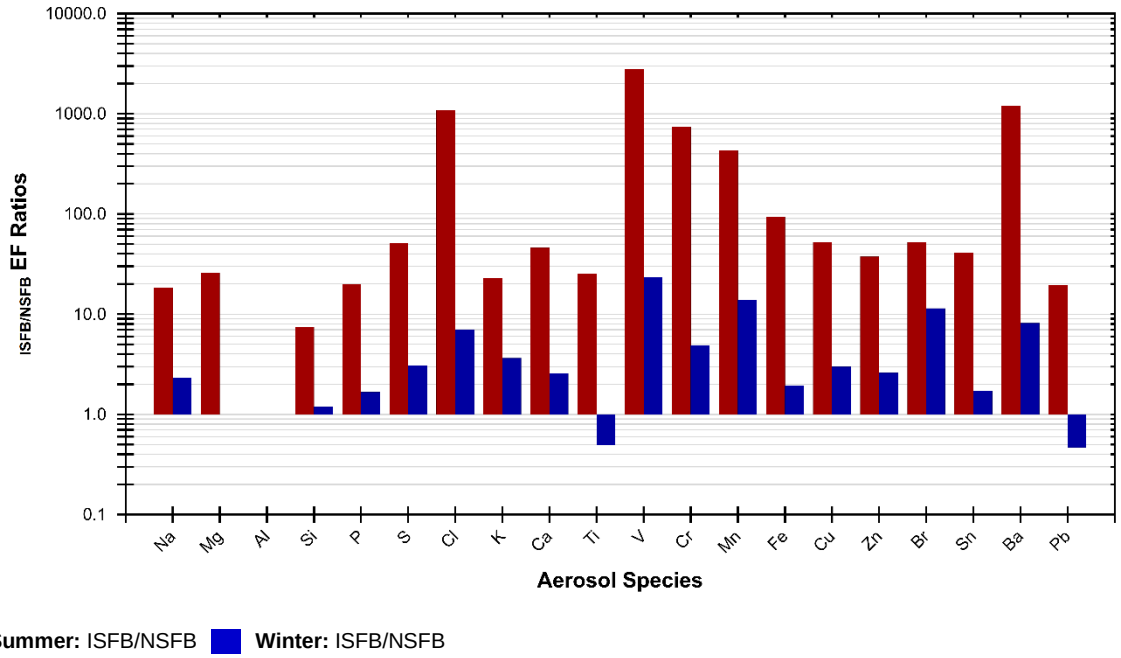

Figure 4.25 ISFB-to-NSFB household ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of coal-burning communities, categorised by season (summer and winter).

Settlement-to-settlement ratios of the crustal EFs within the coal-burning communities

In KwaDela (summer, ISFB dwellings) *(Figure D.5.c)*, Si showed a moderate level of enrichment, while P, Mg, Na, K, Fe, Ca, and Ti were highly enriched. The remaining elements (Mn, S, Cr, Ba, V, Cl, Br, Zn, Cu, Pb, and Sn) were extremely enriched. The mean EFs in KwaZamokuhle *(Figure D.6.c)* varied from that of KwaDela. Low enrichment was observed for Si, Mg, and F while P and Na were moderately enriched. K, Ca, Ti, Mn, Cr, V, S, and Ba were highly enriched with extreme enrichment of Cl, Zn, Cu, Br, Pb, and Sn. During summer *(Figure D.7.c)*, Si, Fe, P, Mg, K, Na, and Ca had low enrichment, while Mn was moderately enriched. High enrichment was observed for Ti, V, Cr, Ba, Cl, and S with extreme enrichment of Br, Zn, Cu, Pb, and Sn. However, during winter *(Figure D.10.c)* the element enrichment increased with only Si and Mg showing low enrichment, while Fe and P were moderately enriched. High enrichment was noted for Na, Ti, K, Ca, Mn, Cr, V, and S. The remaining elements (Ba, Cl, Zn, Cu, Br, Pb, and Sn) were extremely enriched.

The summer-to-winter EF ratios for KwaZamokuhle indicated higher levels of enrichment during summer for almost all the elements. Mg and Ti were close to unity, while Pb (1.54) had higher levels of enrichment during summer. Within KwaZamokuhle, the season-to-season EF ratios for the ISFB/ISFB dwellings *(Figure D.8.c and Figure D.11.c)* indicated that Pb was close to unity, while all the other elements had higher levels of enrichment during winter. Similarly for the NSFB/NSFB household *(Figure D.9.c and Figure D.12.c)* comparison, most of the elements had higher levels of enrichment during the winter. The

Mg (ratio: 1.14), Pb (ratio: 1.22), and Mn (ratio: 1.70) elements had higher levels of enrichment during the summer.

The settlement-to-settlement (KwaDela/KwaZamokuhle) ratios showed that all elements experienced higher levels of enrichment in KwaDela, with ratios ranging between 6.19 (Si) and 108.69 (Mn).

This indicates that the ISFB households in KwaDela will be influenced more significantly by anthropogenic sources, during summer, than KwaZamokuhle. However, in KwaZamokuhle the ISFB- and OSFB houses will show greater variability in its contributing sources than during winter. The winter will also have higher contributions from anthropogenic emission sources than during summer.

4.1.2.3.2. Crustal EFs within the urban community

Looking at the urban community *(Table 4.5 and Figure D.13.c)*, Si, Mg, K, and P show low levels of enrichment. Moderate enrichment was observed for Na and Ca. High EFs were noted for Fe, Ti, Mn, S, Cr, V, and Ba. Extreme enrichment was found for Mn, S, Cr, V, Ba, Cl, Br, Zn, Cu, Pb, and Sn.

Season-to-season ratios of the crustal EFs within the urban community

The summer-to-winter ratios of the enrichment factors for elements measured within the urbanised community are given in *Figure 4.26*. The summer enrichment *(Figure D.14.c)* showed low levels of enrichment for Si, P, Mg, K, and Fe, while Na and Ca were moderately enriched. The Ti, Mn, S, and Cr elements were highly enriched while V, Ba, Cl, Zn, Br, Cu, Pb, and Sn showed extreme enrichment. The winter enrichment *(Figure D.17.c)* varied somewhat from that observed during summer. The low (Si, Mg, K, and P) and moderately (Ca and Na) enriched elements were similar. However, the highly (Ti, Fe, Mn, Ba, V, S, and Cr) and extremely (Cl, Pb, Br, Zn, Cu, and Sn) enriched elements varied somewhat from those observed during the summer. The summer-to-winter EF ratios showed that P, Cr, and Na were close to unity, indicating that these elements do not have significant seasonal variability in the urban community of Jouberton. The Ti, Cl, Ca, K, Mg, Mn, V, Ba, and Pb elements had higher levels of enrichment during the summer, with factors (or ratios) ranging between 1.13 (Ti) and 26.13 (Pb). The remaining elements, namely Fe, Sn, Zn, Cu, Br, and Si experienced higher levels of enrichment during winter, ranging between 0.21 (Fe) to 0.70 (Si).

The summer-to-winter EF ratios *(Figure 4.26)* for the ISFB dwellings showed that Na was close to unity. The majority of the elements (Sn, Zn, Cl, Cu, Br, Fe, Si, Ti, K, P, Ca, and Cr) had increases enrichment during the winter with ratios ranging between 0.12 (Sn) and 0.81 (Cr). A few of the elements (Mg, S, Mn, V, Pb, and Ba) in the ISFB households had higher levels of enrichment during the summer, with ratios ranging between 1.15 (Mg) and 12.36 (Ba). However, the summer-to-winter EF ratio trend for the NSFB dwellings was similar to that of the overall summer-to-winter ratios.

Indoor PM_4 elements experience higher levels of enrichment for Fe, Cu, Zn, Br, and S in both the ISFB- and NSBF households during winter. These element are tracers for a number of anthropogenic sources included, road traffic emission, waste burning and solid fuel burning, all of which were identified during the winter. The elements showing higher levels of enrichment during summer (Mg, V, Mn, Ba, and Pb) are related to road traffics- and waste burning emission. Thus, it is expected that these sources will contribute largely to the indoor PM_4 within both the ISFB-and NSFB households during summer.

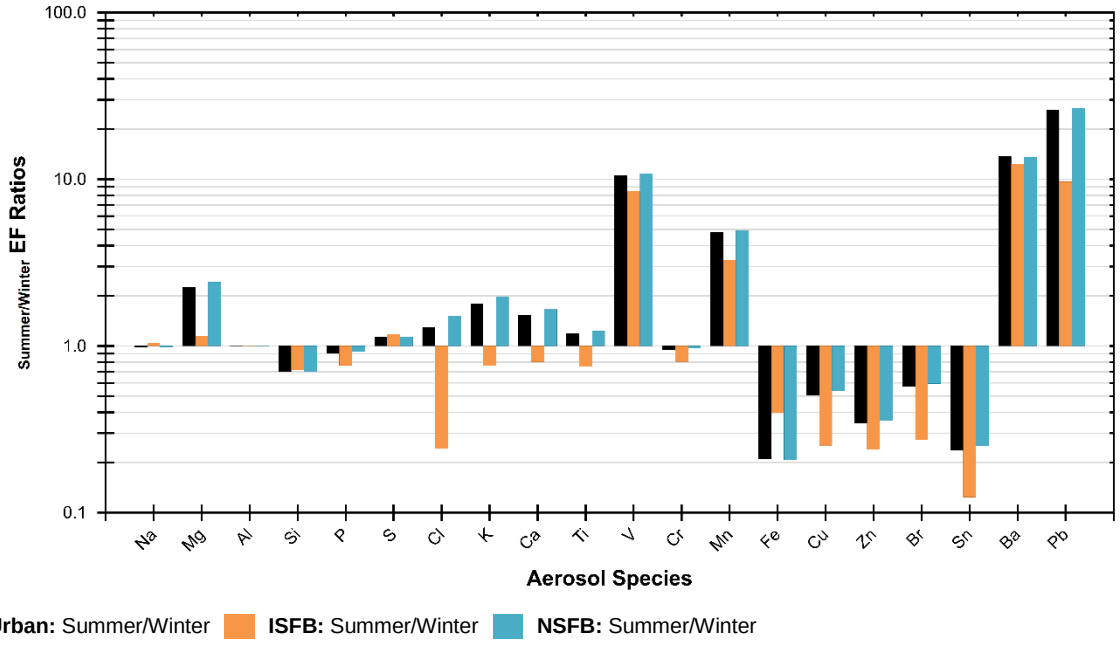

Figure 4.26 Summer-to-winter ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of urbanised-burning communities, categorised by ISFB- and NSFB households.

Household-to-household ratios of the crustal EFs within the urban community

The household-to-household ratios of the element enrichment factors categorised by season are given in *Figure 4.27*. During summer, the ISFB *(Figure D.15.c)* dwellings had experienced low enrichment of Si, Mg, Fe, K, P, and Ti. Both Ca and Na had moderate enrichment. High enrichment was observed for Mn, Cr, S, V, Ba, and Cl. The remaining elements (Br, Zn, Cu, Pb, and Sn) was extremely enriched. The NSFB households *(Figure D.16.c)* had low (Si, P, Mg, K, and Fe) and moderate (Na, Ca) enrichment of the same elements, with the exception of Ti, which was highly enriched in the NSFB. High EFs were observed for Ti, Mn, S, and Cr. The remaining elements (V, Ba, Cl, Zn, Br, Cu, Pb, and Sn) were extremely enriched within the NSFB households. The ISFB/NSFB summer ratios *(Figure 4.27)* indicate that the NSFB dwellings experienced higher levels of enrichment for all elements compared to the ISFB, with the exception of Si which was close to unity.

During winter, the ISFB *(Figure D.18.c)* households had low enrichment of Si Mg, K, P, Ti, and Fe. A few elements, namely Mn, Na, and Ca showed moderate enrichment. The highly enriched elements included

Ba, V, S, Cr, and Pb, while Cl, Br, Zn, Cu, and Sn were extremely enriched. The NSFB *(Figure D.19.c)* dwellings had fewer elements (Si, Mg, K, and P) with low enrichment. Similarly to the ISFB houses, Ca and Na was moderately enriched. High enrichment was observed for Ti, Fe, Mn, Ba, V, S, and Cr. The extremely enriched elements included Cl, Pb, Br, Zn, Cu, and Sn. The ISFB/NSFB EF ratios *(Figure 4.27)* showed that P, Sn, Si and Mg were close to unity, thus the ISF- and NSFB dwellings experienced similar levels of enrichment during winter. Majority of the elements (Ba, V, Mn, Fe, Cr, Ti, Br, Pb, Zn, Cu, Na, and S) had EF ratios below one (<1) indicating higher levels of enrichment in the NSFB houses. A few elements, namely Ca, K, and Cl showed higher enrichment in the ISFB dwellings during winter.

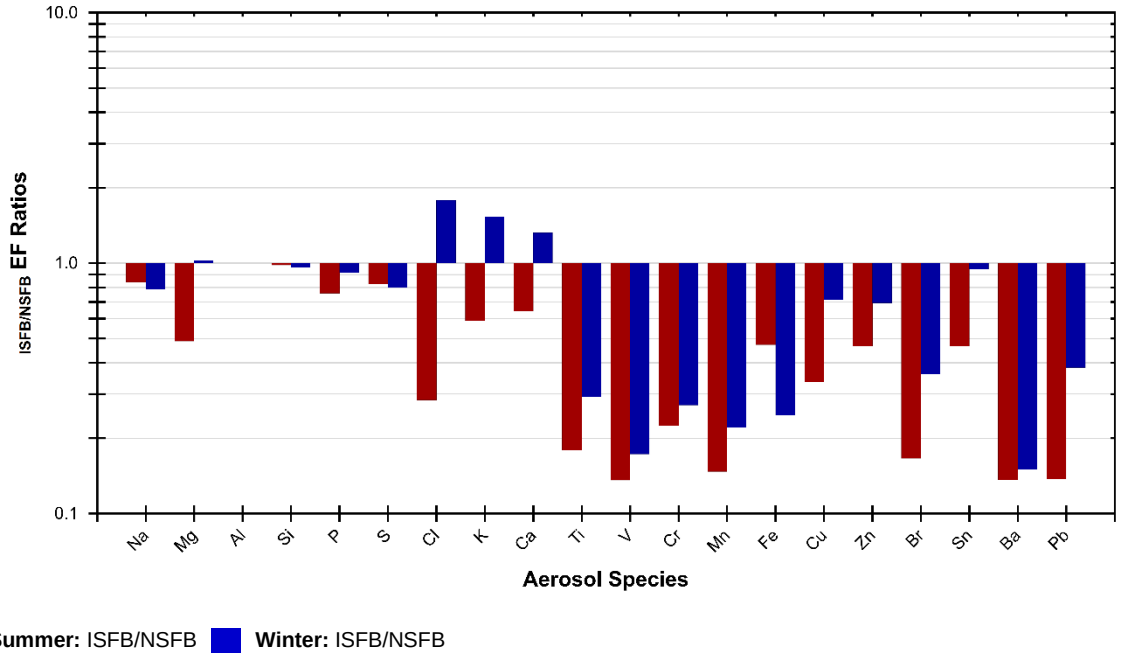

Figure 4.27 ISFB-to-NSFB household ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of urbanised community, categorised by season (summer and winter).

Similar to the urban-community, higher variability in the elemental enrichment, between the ISFB and NSFB houses, is observed during summer compared to winter. It is expected that the source contributions, within the two types of households, will differ more during summer than during winter. Anthropogenic emissions sources are also accepted to be higher contributors than the natural sources. This is supported by the qualitative source apportionment results *(see Figure 4.37 and Figure 4.38 in Section 4.1.2.5).*

4.1.2.3.3. Crustal EFs within the wood-burning communities

The wood-burning communities *(Figure D.20.c)* had low enrichment of Si, Mg, P, and K. Moderate enrichment was observed for Fe, Ti, and Ca. The Mn, Na, V, S, Ba, and Cr elements were highly enriched, while Cl, Br, Zn, Cu, Pb, and Sn showed extreme enrichment.

Season-to-season ratios of the crustal EFs within the wood-burning communities

The season-to-season ratios of the enrichment factors for elements measured within the wood-burning communities are given in *Figure 4.30*. During spring the elementals showed low enrichment for Si, Fe, Mn, Ca, Ti, P, K, and V, while Na and Mg were moderately enriched. The Cr, S, Cl, Br, Zn, and Cu elements were highly enriched with Pb and Sn having extreme enrichment. The summer enrichment *(Figure D.21.c)* showed low levels of enrichment for Si, Mg, and P, while K, Fe, and Ti were moderately enriched. The Ca, Mn, Na, V, Ba, S, and Cr elements were highly enriched with Cl, Br, Zn, Cu, Pb, and Sn showing extreme enrichment. The winter enrichment *(Figure D.22.c)* varied somewhat from that observed during summer. The low (Si, P, Fe, Ti, Mg, K) and moderately (Ca and Mn) enriched elements were similar. However, the highly (Na, S, V, Ba, Cr, and Cl) and extremely (Br, Zn, Cu, Pb, and Sn) enriched elements varied somewhat from those observed during the summer.

The spring-to-summer EF ratios *(Figure 4.28)* indicated that Si was close to unity, while Mg showed higher enrichment during spring. The remaining elements (Cr, V, Cu, Zn, Br, Sn, Cl, Mn, Ca, Fe, Pb, Ti, Na, S, K, and P) had ratios below one (<1) indicating higher levels of enrichment during the summer with the wood-burning communities. The spring-to-winter EF ratios *(Figure 4.29)* showed that Si, Ti, and Pb were close to unity for these seasons. The K (ratio: 1.15), P (ratio: 1.85), and Mg (ratio: 2.41) elements had higher levels of enrichment during the spring compared to winter. However, majority of the elements present (V, Cr, Br, Cu, Mn, Zn, Sn, Cl, Ca, Na, Fe, and S) had increased enrichment during winter. The summer-to-winter EF ratios *(Figure 4.30)* indicated that Si was close to unity, indicating that these elements do not have significant seasonal variability in the wood-burning communities All the elements showed higher levels of enrichment during the summer, with ratios ranging between 1.14 (Mg) to 6.05 (Pb).

The spring-to-summer EF ratios for the ISFB, NSFB, and OSFB households showed a similar trend as the overall spring-to-summer comparison *(Figure 4.28)*. For the ISFB dwellings Si was close to unity, while Mg (ratio: 2.81) had higher levels of enrichment during spring. The remaining elements (Ba, Cr, V, Br, Cu, Sn, Zn, Cl, Mn, Ca, Pb, Fe, Ti, S, Na, P, and K) experienced higher enrichment during the summer. For the NSFB households, Fe, Si, and P were close to unity, while Mg (ratio: 1.83) again showed higher enrichment during spring. Similarly to the ISFB, the majority of the elements (Ba, Cu, Zn, V, Cr, Cl, Sn, Br, Mn, Ca, Na, S, Pb, Ti, and K) had higher levels of enrichment during summer. The OSFB dwelling had similar trends to the ISFB, where Si was close to unity and Mg (ratio 2.01) had higher enrichment during spring. The highest seasonal variation was observed for the OSFB dwellings.

The spring-to-winter EF ratios for the ISFB, NSFB, and OSFB households are given in *(Figure 4.29)*. In the ISFB and NSFB dwellings, both Si and S were close to unity, while K, Ti, P, Pb, and Mg had higher levels of enrichment during spring. The remaining elements experienced higher levels of enrichment during winter. Within the OSFB, only Si was close to unity, while P (ratio: 1.58) and Mg (ratio: 2.38). The majority of the elements (Ba, Cr, V, Sn, Cu, Zn, Br, Cl, Mn, Na, Ca, S, Fe, Pb, Ti, and K) showed increased enrichment during the winter.

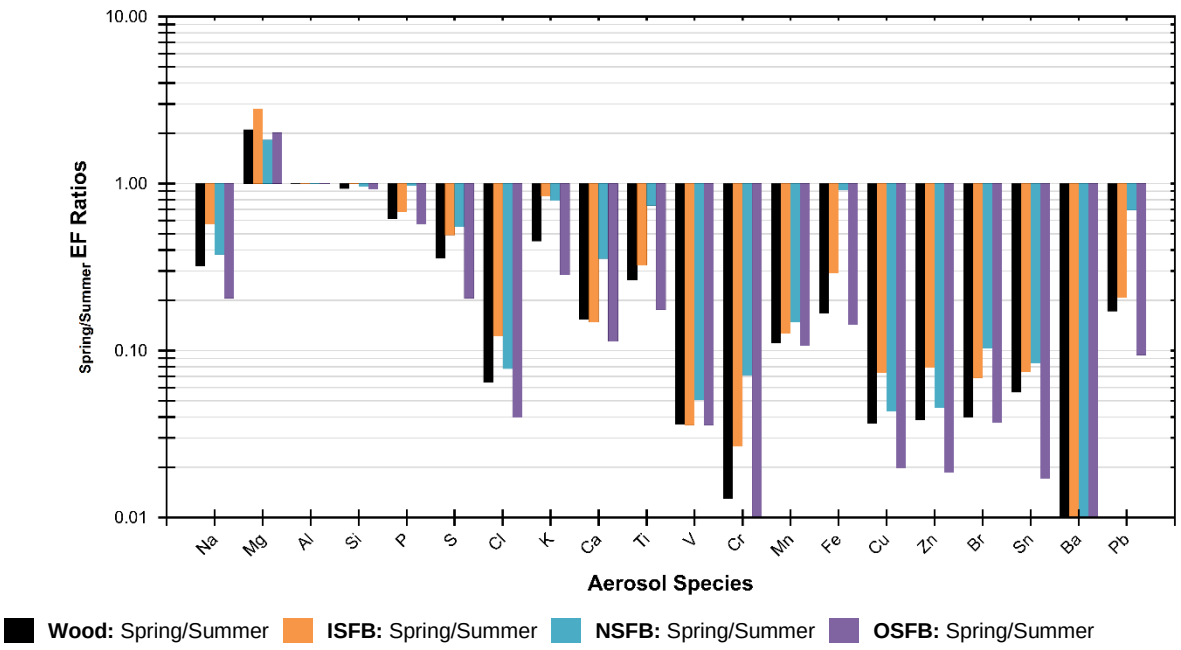

Figure 4.28 Spring-to-summer ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of wood-burning communities, categorised by ISFB-, NSFB- and OSFB households.

The summer-to-winter ratios for the ISFB, NSFB, and OSFB households showed a similar trend as the overall summer-to-winter comparison *(Figure 4.30)*, with the exception of a few specific elements. For the ISFB dwellings the Si, Mg, and Na elements were close to unity, while V (ratio: 0.51) had higher levels of enrichment during the winter. The remaining elements (Mn, K, Br, Fe, Ba, Cr, S, Cu, Zn, P, Sn, Cl, Ca, Ti, and Pb) experienced higher enrichment during the summer, with ratios ranging between 1.11 (Mn) and 9.66 (Pb). For the NSFB households, Mn, Si, and Mg were close to unity, while Pb (ratio: 0.53), V (ratio: 0.66), Ti (ratio: 0.77), and Br (ratio: 0.84) had higher levels of enrichment during the winter. The remaining elements (Ca, Fe, Na, K, Cr, P, S, Sn, Ba, Cu, Cl, and Zn) experienced higher enrichment during the summer, with ratios ranging between 1.17 (Ca) and 4.27 (Zn). Within the OSFB houses, Ba and Si were close to unity. All the other elements (Mg, Na, V, Mn, S, Ca, P, K, Cl, Br, Sn, Ti, Cu, Zn, Fe, Cr, and Pb) showed higher levels of enrichment during summer with ratios ranging between 1.19 (Mg) and 8.21 (Pb). Thus, the ISFB households showed less seasonal variation in the level of elemental enrichment, followed by the OSFB- and ISFB dwellings.

The largest seasonal variability in the level of enrichment was observed between spring and summer. This indicates that the indoor PM_4 experienced higher levels of enrichment during summer, with the exception of Mg. The winter season also experiences higher levels of enrichment, compared to spring. However, the differences in the level of enrichment is smaller (thus, lower ratios during winter). Mg is associated with wood- and biomass burning. Due to the small filter sample size for spring, it was not possible to resolve the qualitative source contribution, however, the assumption is that biomass burning is a larger contributor during spring as a result of regional biomass burning events. The elements experienced higher enrichment

during summer, compared to winter. The NSFB and OSFB dwelling showed higher differences in elemental enrichment than the ISFB houses, indicating higher variability in it possible emission source contributions.

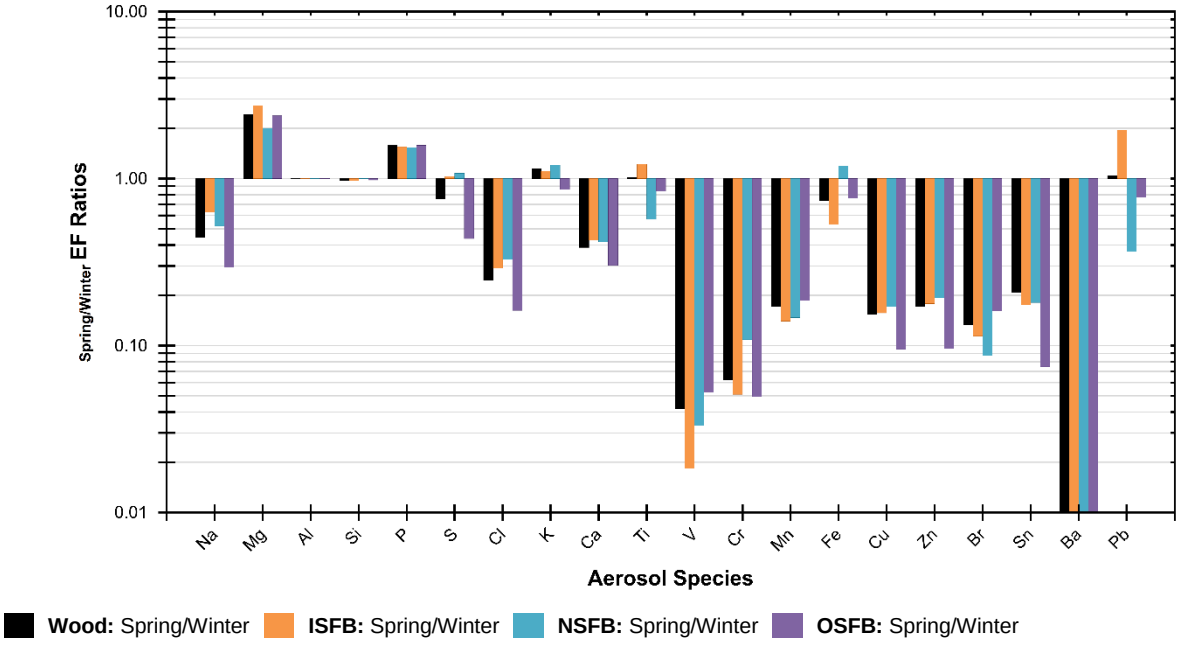

Figure 4.29 Spring-to-winter ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of wood-burning communities, categorised by ISFB-, NSFB- and OSFB households.

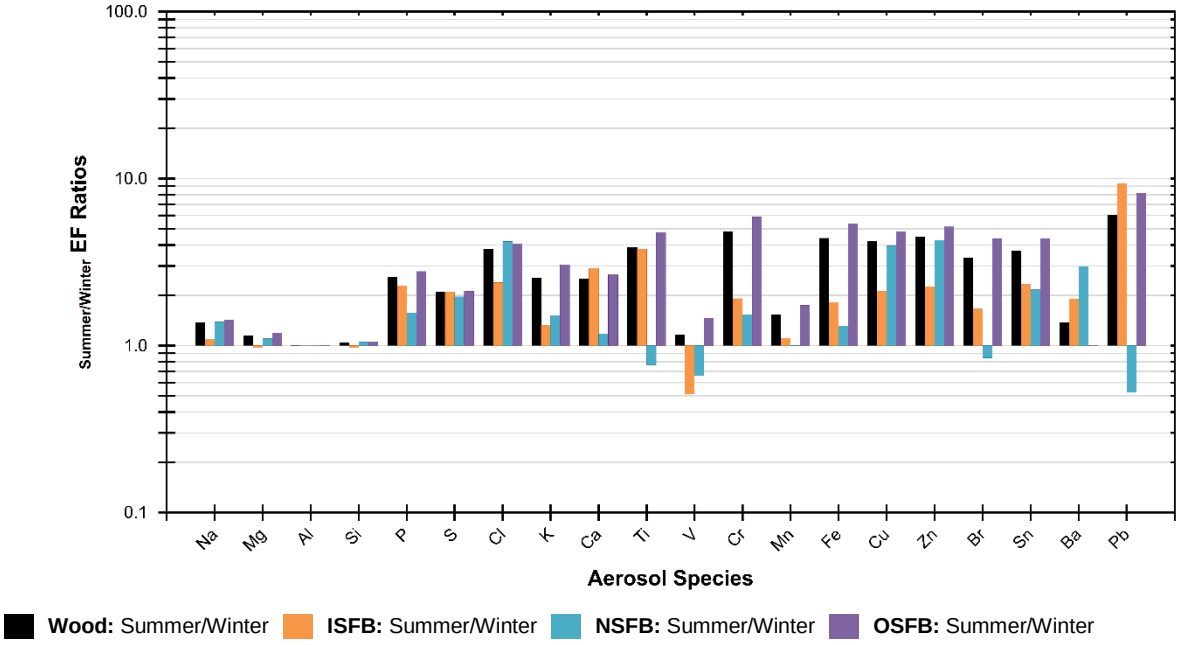

Figure 4.30 Summer-to-winter ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of wood-burning communities, categorised by ISFB-, NSFB- and OSFB households.

Household-to-household ratios of the crustal EFs within the wood-burning communities

The seasonal household-to-household enrichment factor ratios for the ISFB/NSFB, ISFB/OSFB, and NSFB/OSFB are shown in *Figure 4.31*, *Figure 4.32* and *Figure 4.33*.

The ISFB/NSFB ratios *(Figure 4.31)* indicated that during spring, Cr, Br, Ca, Si, Mg, and P were close to unity for both the ISFB and NSFB dwellings. V, Mn, Fe, and Sn showed higher levels of enrichment within the NSFB houses. The ISFB households showed increased enrichment of S, Ti, K, Na, Cl, Cu, Zn, and Pb. During summer, Si and Sn were close to unity. Ba, Mg, V, Cu, Zn, Cl, Na, and Mn experienced higher levels of enrichment in the NSFB dwellings, with ratios ranging between 0.36 (Ba) and 0.89 (Mn). The remainder of the elements (K, S, Br, P, Ca, Cr, Fe, Ti, and Pb) showed higher enrichment in the ISFB houses, with ratios ranging between 1.20 (K) and 4.67 (Pb).

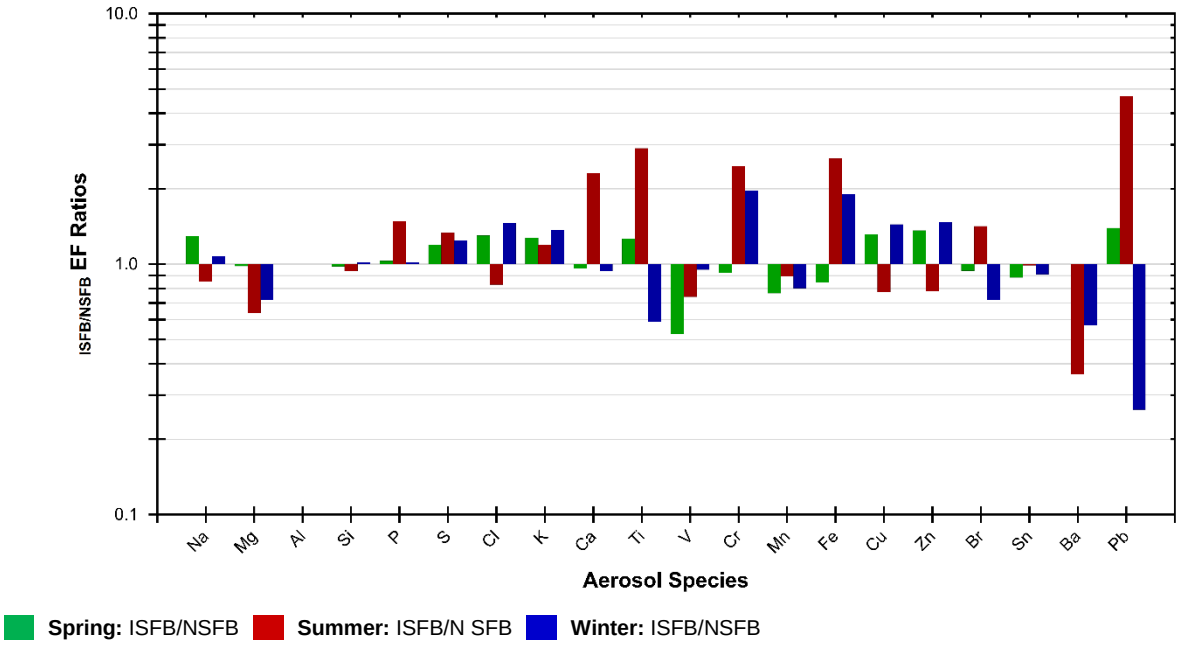

Figure 4.31 ISFB-to-NSFB household ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of wood-burning communities, categorised by season (spring, summer and winter).

During winter, the ISFB/OSFB ratios for Sn, Ca, V, Si, P, and Na was close to unity indicating little difference in the level of enrichment of these elements between the two household classifications. The ISFB houses showed higher levels of enrichment for P, Na, S, K, Cu, Cl, Zn, Fe, and Cr with rations ranging n between 1.24 (S) and 1.97 (Cr). The remaining elements (Ti, Pb, Ba, Br, Mg, and Mn) had higher levels of enrichments in the NSFB houses during winter.

The ISFB/OSFB EF ratios *(Figure 4.32)* for spring indicated that Si, Mg, and P were close to unity, while V, Mn, Br, and Fe showed increased enrichment in OSFB dwellings. The Cr, Ca, Ti, K, Na, Cl, S, Cu, Pb,

Zn, and Sn elements had higher levels of enrichment in the NSFB dwellings, with ratios ranging between 1.36 (Cr) and 3019 (Sn). During summer, the ISFB/OSFB ratios indicated that S, Ti, Ca, and Pb was close to unity, while Ba (ratio: 1.31) had higher enrichment within the ISFB households. The majority of the elements (Fe, Cr, Br, V, K, Cu, Zn, Cl, Na, Mn, Mg, Sn, P, and Si) were more enriched in the OSFB dwellings with ratios ranging between 0.43 (Fe) and 0.89 (Si). During winter, S, Pb, Si, Ca, P, Mn, and Cl was close to unity. A few elements (Ba, Mg, and Na) had higher levels of enrichments in the OSFB houses. The remaining elements (Br, Ti, Fe, Cr, Sn, K, V, Cu, and Zn) had higher levels of enrichment in the ISFB households with ratios ranging between 1.18 (Br) and 1.46 (Zn).

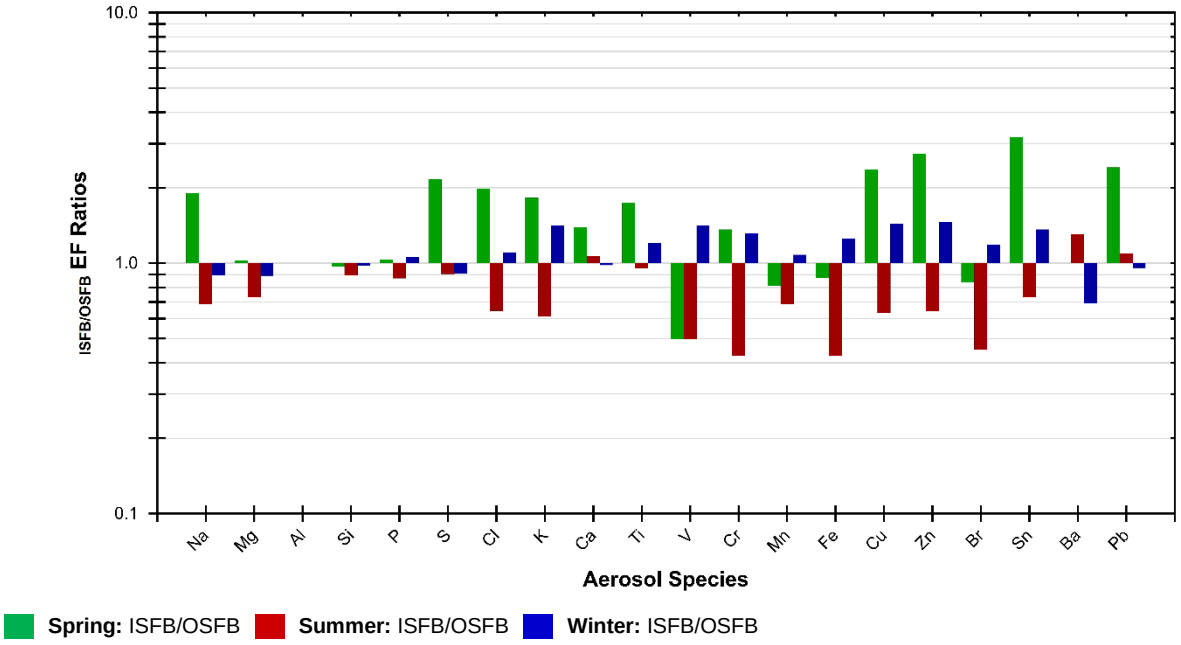

Figure 4.32 ISFB-to-OSFB household ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of wood-burning communities, categorised by season (spring, summer and winter).

The NSFB/OSFB EF ratios *(Figure 4.33)* for spring showed that V, Si, P, Fe, Mg, and Mn were close to unity, while Br shad higher enrichment in the OSFB dwellings. The Ti, K, Ca, Na, Cr, Cl, Pb, Cu, S, Zn, and Sn experienced higher enrichment within the NSFB households. During summer, the ratios indicated that Si was close to unity, while Mg (ratio: 1.15) and Ba (ratio: 3.59) had higher levels of enrichment in the OSFB dwellings. All the other elements (Fe, Cr, Pb, Br, Ti, Ca, K, P, V, S, Sn, Mn, Cl, Na, Cu, and Zn) had ratios below one (<1) indicating higher levels of enrichment in the NSFB households during summer. During winter, the Si, Zn, Cu, K, P, and Ca elements were close to unity for the NSFB- and OSFB houses. The NSFB dwellings experienced higher levels of enrichment for Ba, Mg, Mn, V, Sn, Br, Ti, Pb with ratios ranging between 1.21 (Ba) and 3.65 (Pb). The remaining elements (Fe, Cr, S, Cl, and Na) had higher levels of enrichment within the OSFB households during winter.

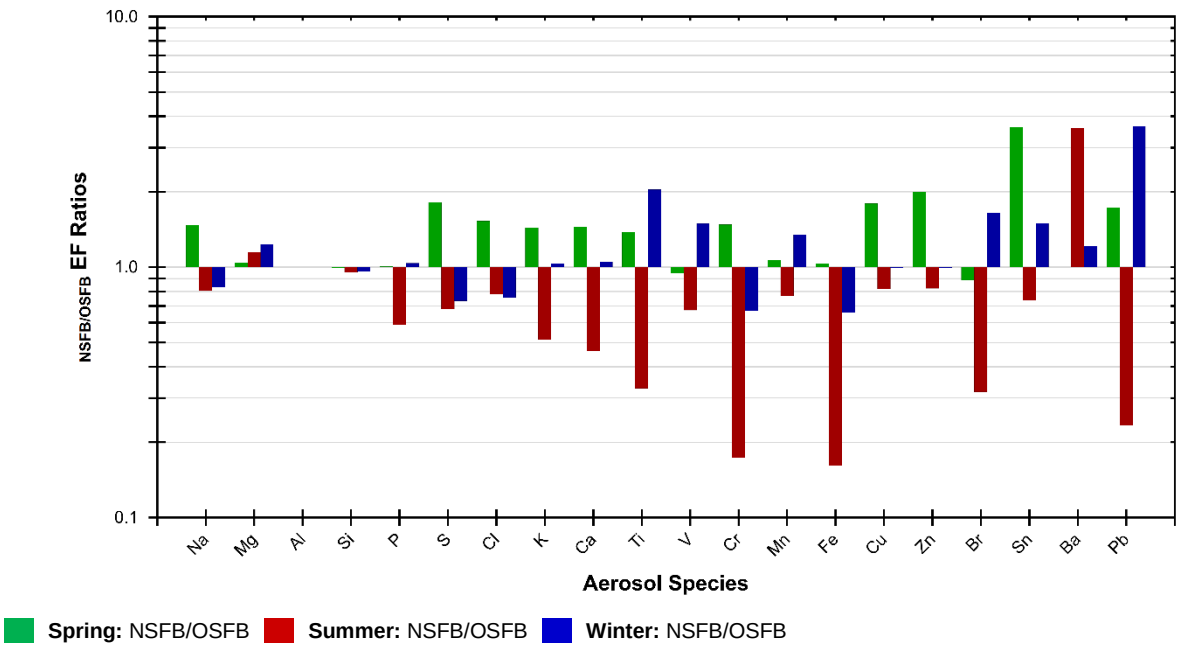

Figure 4.33 NSFB-to-OSFB household ratios of mean elemental enrichment factors (EFs) for the residential indoor environment of wood-burning communities, categorised by season (spring, summer and winter).

The spring and winter exhibited similar trends, as the majority of elements had higher levels of enrichment within the ISFB households. Elements such as Zn, Sn, and K had increased enrichment in the ISFB houses, indicating road traffic-, waste burning-, and biomass combustion emission might be higher within these households. The inverse is true for the summer, whereby the all elements, excluding Ba and Pb, showed higher enrichment in the OSFB dwellings, which could possibly be linked to higher contributions from road traffic-, waste burning- and residential solid fuel combustion emission.

Settlement-to-settlement ratios of the crustal EFs within the wood-burning communities

In Agincourt *(Figure D.23.c)*, Si, Mg, P, Fe, K, and Ti showed low levels of enrichment, while Ca was moderately enriched. The Mn, Na, V, S, Ba, and Cr were highly enriched with Cl, Br, Zn, Cu, Pb, and Sn showing extreme enrichment. During summer *(Figure D.24.c)*, Si, Mg, P, and Fe had low enrichment, with K and Ti showing moderate enrichment. The Ca, Mn, Na, V, S, Ba, and Cr elements were highly enriched. Extreme enrichment was identified for the same elements as for the overall mean. During winter *(Figure D.28.c)*, Si, P, Ti, Fe, Mg, and K had low enrichment. Moderate enrichment was observed for Ca and Mn, while Na, S, V, Ba, Cr, and Cl were highly enriched. The remainder of the elements (Br, Pb, Zn, Cu, and Sn) were extremely enriched. Similarly to the overall summer-to-winter EF ratios, the summer had higher levels of enrichment than the winter, with ratios ranging between 1.12 (V) and 6.89 (Pb).

Within Agincourt, the season-to-season EF ratio trend for the ISFB/ISFB comparison *(Figure D.25.c and Figure D.29.c)* was similar to the overall wood-burning community ratios above. This is also true for the

NSFB/NSFB household comparison *(Figure D.26.c and Figure D.30.c)*. For the OSFB/OSFB comparison *(Figure D.27.c and Figure D.31.c)* the ratios were similar to the overall wood-burning community ratios. Mn, Mg, Si, and Ti were close to unity. Pb and V had ratios below one (<1) indicating higher enrichment in the winter. All the remaining elements had higher levels of enrichment during the summer with ratios ranging between 1.17 (Na) and 5.70 (Zn).

In Giyani *(Figure D.32.c)*, Si, Mn, P, and K showed low levels of enrichment, while Mg and Ca was moderately enriched. The Ti, Na, Fe, V, Ba, and S elements were highly enriched with Cl, Cr, Br, Zn, Cu, Pb, and Sn showing extreme enrichment. During summer *(Figure D.33.c)*, Si had low enrichment, with P, K, Mn, Mg, and Ca showing moderate enrichment. High enrichment was observed for Ti, Na, Fe, Ba, V, and S while Cl, Br, Cr, Zn, Cu, Pb, and Sn were extremely enriched. The winter enrichments varied somewhat from the summer. During winter *(Figure D.36.c)*, Si, Fe, Mn, P, K, Mg, Ti, and Ca showed low enrichment, while Na was moderately enriched. High enrichment was observed for V, Ba, Cr, S, and Cl with extreme enrichment of Zn, Cu, Br, Pb, and Sn. Similarly to Agincourt, Giyani experienced higher levels of enrichment during the summer. However, the ratios in Giyani were much higher, ranging between 1.74 (Ca) and 214.62 (Cr). This indicated that there is a higher season variability in Giyani than in Agincourt.

The summer-to-winter EF ratios fir Giyani varies from that observed for Agincourt. Si and Mg were close to unity in the NSFB *(Figure D.34.c and Figure D.37.c)* households. S, Cl, Mn, and Na had ratios above one (>1) indicating higher levels of enrichment during the summer, whereas Br, Ca, Cr, Sn, Zn, Cu, V, Pb, Ti, K, P, Ba, and Fe were higher during winter. For the OSFB/OSFB dwelling comparison *(Figure D.35.c and Figure D.38.c)*, the EF ratios indicate that Si was close to unity. Al the other elements showed increased enrichment during the summer with ratios ranging between 2.20 (Mg) and 64.23 (Cr).

The settlement-to-settlement (Agincourt/Giyani) ratios only a single element, namely K, was close to unity for these two settlements. Majority of the elements (Si, Cl, Br, Ca, V, Sn, Zn, Cu, Ba, and Mn) had ratios above one (>1), ranging between 1.13 (Si) and 3.39 (Mn), which indicate that these elements had higher levels of enrichment in Agincourt. The remainder of the elements (Cr, Fe, Ti, Pb, Mg, Na, P, and S) had a higher level of enrichment in Giyani. Based on the above, biomass burning and road traffic emissions are likely the largest contributors to indoor PM_4 within Giyani, whereas Agincourt has a more diverse set of contributing sources.

The variations in the elemental enrichment factors found within the residential indoor environment were investigated based on the community, settlement, season and household fuel use classification. These ratios provided an initial impression of whether the sources contributing to the indoor environment were of a natural or anthropogenic nature. It was found that both natural and anthropogenic sources contributed to the residential indoor environment is the low-income communities in South Africa. The EF ratios showed

some similarities in the level of elemental enrichment in the urban- and wood burning communities, whereas the coal-burning communities experienced much higher EFs. This leads to the assumption that anthropogenic sources are more dominant within the coal-burning communities, whereas naturally occurring sources contribute more to particulate matter within he urban- and rural wood-burning communities. The relationship that exists between the elements is discussed in further detail in the following section.

4.1.2.4. Correlation analysis investigating the relationship between the indoor PM_4 elements and possible source types

The relationship that exists between the above-mentioned elements is a good indicator of which elements might originate from the same source and how many sources could actually be contributing to these elements. The correlation coefficients that exists between the elemental mass concentrations of PM_4 within the residential indoor environment within the low-income communities are shown in *Table 4.6*. The elements displayed both weak and strong positive, as well as, negative correlations.

4.1.2.4.1. Crustal soil elements

Silicon (Si) and aluminium (Al) are the most abundant trace elements of crustal material. Elements that have a good correlation with either Si or Al were regarded as originating from the same emission source, these elements are referred to as ***"crustal soil elements"***. For the purpose of this discussion the correlation coefficients of the various elements to Si is shown in *Figure 4.34.a*. The elements with very strong positive (r^2:≥ 0.8) correlations consisted of Al (r^2: 0.99) and Mg (r^2:0.86), while there was a strong positive (r^2: ≥ 0.6 to <0.8) correlation with K (r^2: 0.77), P (r^2: 0.73), Na (r^2: 0.70) and Ca (r^2:0.64). In addition, there is a moderate positive (r^2: ≥0.4 to <0.6) correlation with S (r^2: 0.45), while there is a very weak positive correlations identified for both Fe (r^2: 0.15) and Ti (r^2: 0.08).

The main crustal soil element (Al, Mg, K, P, Na, Ca, and S) are thus the main contributors to crustal soil emissions *(Maenhaut et al., 1996)*. Even though these elements are predominantly related to crustal soil, it does not exclude other sources from contributing to its atmospheric loading.

Based on the Al/Si scatter associated with the correlation coefficient, it is clear that Al has a single dominating source *(Figure 4.34.b)*, namely crustal soil. However, this was not the case for the remaining contributing elements. The Mg/Si and Ca/Si scatter indicates that there are at least two sources, of which crustal soil is one, contributing to Mg *(Figure 4.34.c)* and Ca *(Figure 4.34.g)* in the respirable particulate fraction. The K/Si *(Figure 4.34.d)*, P/Si *(Figure 4.34.e)*, Na/Si *(Figure 4.34.f)*, and S/Si *(Figure 4.34.h)* scatter show at least three possible contributing sources, including crustal soil, to each of the elements.

Table 4.6 The result of the elemental correlation coefficients between the elemental mass concentrations (µg.m^{-3}) of PM_4 measured in the residential indoor environments of low-income settlement in South Africa between 2015 and 2017 (***Note***: those that only the significant coefficients at p-value <0.5 are indicated in bold).

Colour Scale for correlation coefficients:

-1.0	-0.8	-0.6	-0.4	-0.2	0.0	0.2	0.4	0.6	0.8	1.0

	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Cu	Zn	Br	Sn	Ba	Pb
Na																				
Mg	**0.77**																			
Al	**0.65**	**0.85**																		
Si	**0.70**	**0.86**	**0.99**																	
P	**0.48**	**0.72**	**0.74**	**0.73**																
S	**0.16**	**0.36**	**0.48**	**0.45**	**0.35**															
Cl																				
K	**0.56**	**0.74**	**0.77**	**0.77**	**0.82**	**0.39**														
Ca	**0.53**	**0.70**	**0.65**	**0.64**	**0.62**			**0.64**												
Ti		**0.18**					**0.73**		**0.52**											
V			**-0.23**	**-0.24**	**-0.24**		**0.91**			**0.79**										
Cr	**0.06**																			
Mn	**-0.13**		**-0.18**	**-0.20**	**-0.22**		**0.91**			**0.79**	**0.98**									
Fe	**0.17**	**0.15**	**0.16**	**0.15**								**0.97**								
Cu	**-0.26**	**-0.17**	**-0.29**	**-0.31**	**-0.25**		**0.88**			**0.85**	**0.95**		**0.93**							
Zn	**-0.28**	**-0.18**	**-0.28**	**-0.31**	**-0.19**		**0.84**			**0.85**	**0.89**		**0.86**		**0.98**					
Br	**-0.18**	**-0.12**	**-0.21**	**-0.22**	**-0.15**		0.44			**0.51**	0.49				**0.57**	**0.57**				
Sn	**-0.23**	**-0.15**	**-0.22**	**-0.24**			**0.56**			**0.59**	**0.58**				**0.67**	**0.70**				
Ba	**-0.24**	**-0.15**	**-0.26**	**-0.29**	**-0.25**		**0.90**			**0.77**	**0.99**		**0.97**		**0.95**	**0.90**		**0.60**		
Pb	**-0.25**	**-0.15**	**-0.26**	**-0.30**	**-0.24**		**0.68**			**0.91**	**0.78**		**0.75**		**0.90**	**0.90**	**0.57**	**0.64**	**0.78**	

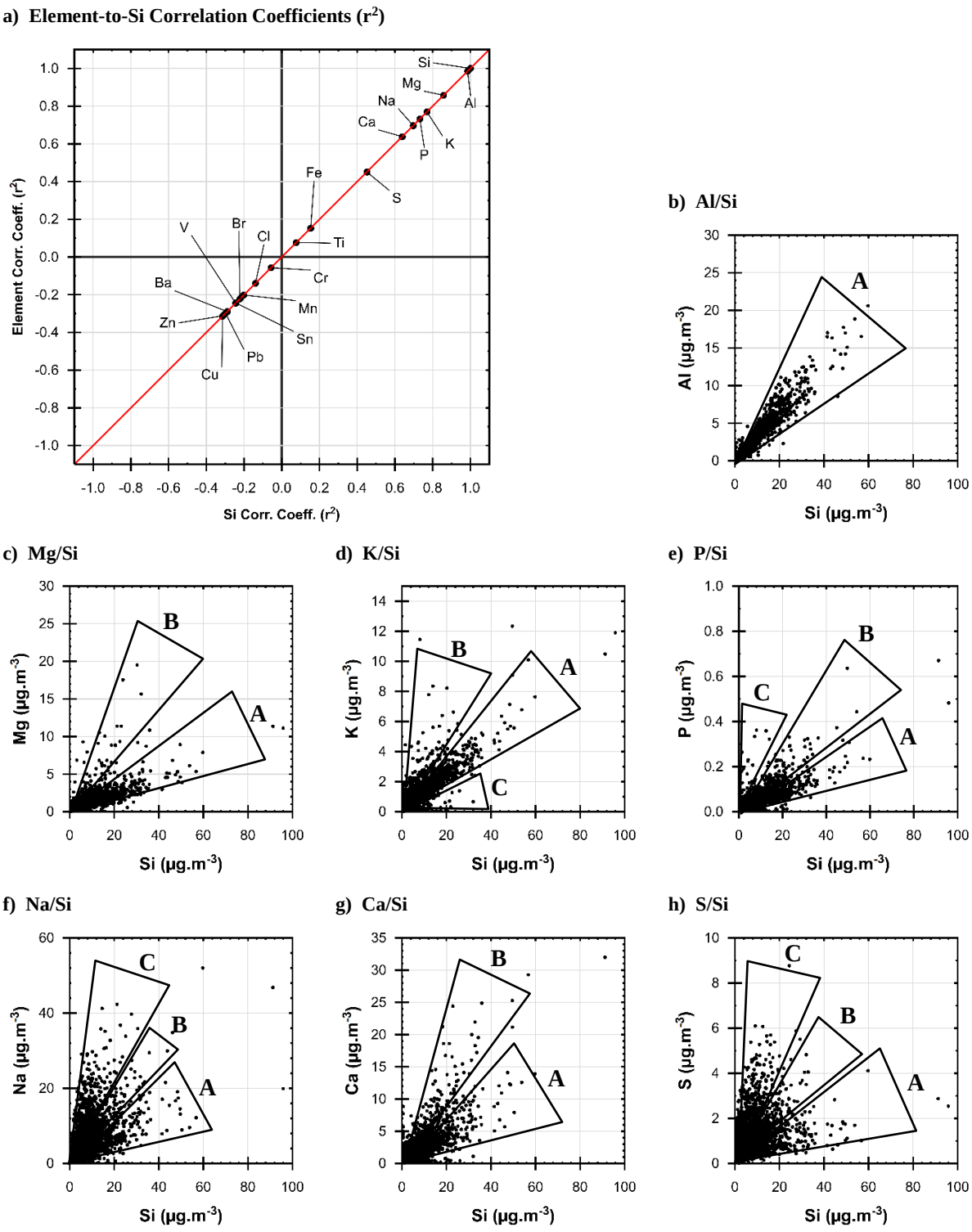

Figure 4.34 Correlation coefficients of a) the individual elements against silicon (Si) and the scatter plots of the main crustal soil elements b) Al, c) Mg, d) K, e) P, f) Na, g) Ca, and h) S to silicon (Si) for PM_4 within the residential indoor environment. The triangles A, B, and C indicate the number possible sources contributing to the elements.

The remaining elements were weakly (r^2: ≥ 0.2 to <0.4) to very weakly (r^2: < 0.2) correlated with Si *(Figure 4.34.a)*. There was a weak negative correlation for Cu (r^2: -0.31), Zn (r^2: -0.31), Pb (r^2: -0.30), Ba (r^2: -

0.29), V (r^2: -0.24), Sn (r^2: -0.24), Br (r^2: -0.22), and Mn (r^2: -0.20). The Cl (r^2: -0.14) and Cr (r^2: -0.06) elements had very weak negative correlations with Si. These negative relationships suggest that these elements mainly originate from entirely different sources related to anthropogenic activities. This statement is supported by the level of enrichment observed and discussed in the previous section. The relationship between these anthropogenic elements is investigated further.

4.1.2.4.2. Road traffic elements

Zinc (Zn) is regarded as a tracer element for emissions resulting from road traffic, which includes various sources such as brake- and tire dust, both gasoline- and diesel vehicle emissions, as well as paved road dust *(De Miguel et al., 1997)*. Thus elements that correlate with Zn are likely to have the same origin *(Thorpe & Harrison, 2008)*. These elements are referred to as ***"road traffic elements"***. The correlation coefficients of the various elements to Zn is shown in *Figure 4.35.a.* It consisted of Cu (r^2: 0.98), Ba (r^2:0.90), Pb (r^2: 0.90), V (r^2: 0.89), Mn (r^2: 0.86), Ti (r^2: 0.85), and Cl (r^2: 0.84). In addition, there is a strong positive correlation with Sn (r^2:0.70) and a moderate correlation with Br (r^2: 0.57). A weak positive correlation was observed with Ca (r^2: 0.26), while Cr (r^2: 0.14), S (r^2: 0.03), and K (r^2: 0.01) had very weak positive correlations. Even though road traffic emissions *(Ezeh et al., 2017)* are the main contributors toward atmospheric Zn and Cu, other contributing emission sources could include heavy metal industries and waste. This is observed in the scatter relationship for Ba/Zn, V/Zn, Mn/Zn, and Ti/ Zn which indicate that the presence of Ba, V, Mn, and Ti are influenced by at least two contributing sources. The Pb/Zn and Cl/Zn scatters show at least three possible contributing sources, including road traffic emission, to each of the elements. The remaining elements were all negatively correlated with Zn, having weak (Si, Al, and Na) to very weak (P, Mg, and Fe) correlations. This supports the assumption that these elements originate from different sources than Zn.

4.1.2.4.3. Solid fuel combustion elements

Lead (Pb) is linked as a tracer element to coal combustion *(Block & Dams, 1975).* Thus, elements that highly correlate with Pb are considered to have similar origins *(Figure 4.35.b)*. These elements are referred to as ***"solid fuel combustion element"***. The elements with a very strong positive correlation included Zn (r^2: 0.90), Cu (r^2: 0.90), and Ti (r^2: 0.91). Strong positive correlations with Pb existed for V (r^2: 0.78), Ba (r^2: 0.78), Mn (r^2: 0.75), Cl (r^2: 0.68) and Sn (r^2:0.64). Br (r^2: 057) showed a moderate positive correlation, while Ca (r^2: 0.23) had a weak positive correlation. Cr (r^2: 0.08) and S (r^2: 0.02) were very weakly correlated with Pb. The remaining elements were all negatively correlated with Sn, having weak (Si, Al, Na, and P) to very weak (Mg, Fe, and K) correlations. This supports the assumption that these elements originate from different sources than Pb.

4.1.2.4.4. Waste burning elements

Tin (Sn) is regarded as a tracer for emissions resulting from waste burning activities *(Kumar et al., 2015, 2018).* Thus, elements that correlate strongly with Sn are likely to originate from similar sources *(Figure 4.35.c)*. These elements are referred to as ***"waste burning elements"***. The elements with strong positive correlations consisted of Zn (r^2: 0.70), Cu (r^2: 0.67), Pb (r^2: 0.64), and Ba (r^2: 0.60). The Ti (r^2: 0.59), V (r^2: 0.58), Mn (r^2: 0.56), Cl (r^2: 0.56), and Br (r^2: 0.41) elements showed moderate positive correlations with Sn. There was a very weak positive correlation with Ca (r^2: 0.15), Cr (r^2: 0.06), and S (r^2: 0.02). The presence of various metals is influenced by the composition of the waste being burned as it often includes a mixture of rubbers, plastics, and metals *(Nagpure et al., 2015)*, all of which release toxic emissions. The remaining elements were all negatively correlated with Sn, having weak (Si, Na, and Al) to very weak (Mg, P, Fe, and K) correlations. This supports the assumption that these elements originate from different sources than Sn.

4.1.2.4.5. Biomass burning elements

Sodium (Na), chlorine (Cl), and potassium (K) are considered to be tracer elements for biomass burning related sources *(Maenhaut et al., 2002)*. Elements that have a strong correlation with Na, Cl, and K were regarded as having the same origin. These elements are referred to as ***"biomass burning elements"***.

Excluding the main crustal elements (Si and Al), the elements that have a strong positive correlation with Na *(Figure 4.35.d)* included Mg (r^2: 0.77). Moderately strong positive correlations were observed for K (r^2: 0.56) and Ca (r^2: 0.53). P (r^2: 0.48) showed weak positive correlation, while Fe, S, Cr, Cl, and Ti were very weakly correlated. The remaining elements were weakly (Zn, Cu, Pb, Ba, and Sn) to very weakly (Br, V, and Mn) negatively correlated with Na.

The elements that have a very strong positive correlation with Cl *(Figure 4.35.e)* include V (r^2: 0.91), Mn (r^2: 0.91), Ba (r^2: 0.90), Cu (r^2: 0.88), and Zn (r^2: 0.84). A strong positive correlation excited with Ti (r^2: 0.73) and Pb (r^2: 0.68), while Sn (r^2: 0.56) and Br (r^2:0.44) had a moderate positive correlation. A weak positive correlation was present for Ca (r^2: 0.37) and Cr (r^2: 0.20). K (r^2: 0.15), Fe (r^2: 0.08), Na (r^2: 0.03), and Mg (r^2: 0.03) had very weak positive correlations with Cl. The remaining elements (Si, Al, P, and S) had very weak negative correlations with Cl.

K *(Figure 4.35.f)* had a very strong positive correlation with P (r^2: 0.82), while Si (r^2: 0.77), Al (r^2: 0.77), Mg (r^2: 0.74), and Ca (r^2: 0.64) had strong positive correlations. Na (r^2: 0.56) was moderately correlated with K. Weak positive correlation was observed for S (r^2: 0.39) and Ti (r^2: 0.29), while Fe, Cl, Cr, Mn, Zn, and Br had very weak correlations. The remaining elements (Ba, Pb, Sn, Cu, and V) had a very weak negative correlation with K.

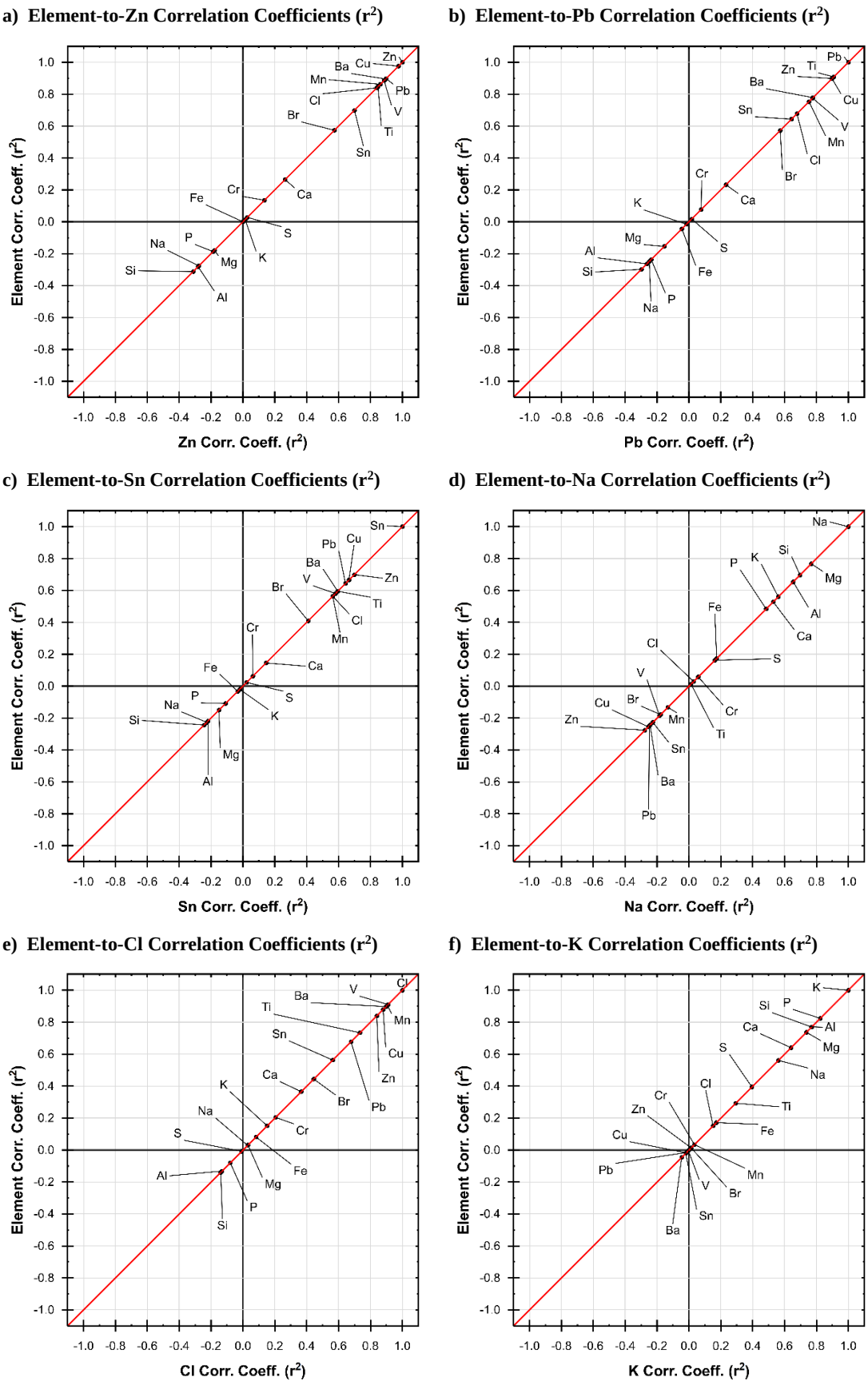

Figure 4.35 Correlation coefficients of the individual elements against a) zinc (Zn), b) lead (Pb), c) tin (Sn), and d) potassium (K) within the residential indoor environment.

The correlations presented above support the idea that multiple sources contribute to the individual PM_4 elemental mass concentrations within the indoor environment of low-income residential settlements in South Africa. The fact that there are multiple source makes it difficult to identify specific sources based on trace elements, as any one element could have multiple contributing sources, this is especially true for environment with many anthropogenic sources. Thus, the tracer element are subjectively selected based on available literature and source profiles. This might cause a bias in the interpretation of the following source apportionment analysis, as South Africa lacks its own source profiles for both the ambient and indoor environments.

The relationships discussed above are expected to vary when considering the community, settlement, season, and household fuel use categorisation. These variations are considered during the interpretation of the principal component analysis (PCA).

4.1.2.5. Qualitative source contributions to indoor PM_4

The principal components analysis (PCA), as described in *Chapter 2 Section 2.5.2.1*, was performed of the elemental data. Additionally, cluster analysis was performed to support the interpretation of the PCA. The analysis was categorised by community, settlement, season and household solid fuel use. The PCA outputs and cluster analysis Dendrograms are presented in *Appendix D*. Note that the PCA was unable to resolve the spring source contributions due to the small sample size, however, the spring samples were included in the overall analysis for the wood-burning communities. The factors identified by PCA were grouped according to the five main source categories discussed in the previous section, namely crustal soil, road traffic, solid fuel combustion, waste-, and biomass burning. These result are discussed in further detail.

The main factors contributing to PM_4 loadings within the residential indoor environment of low-income communities are present in *Figure D.1.a and b*. Based on the PCA, four main factors explain 75.81% of the variability associated with the elemental mass concentration.

Factor one (1) accounted for 33.57% of the variability and was identified as combination of combustion and road traffic emissions. The V, Ba, Mn, Cu, Cl, Pb, Zn, and Ti elements had correlation coefficients >0.5 with associated enrichment factors (EFs) *(Figure D.1.a)* ranging from high to extreme, indicating anthropogenic sources. The combustion related emission could be attributed to sources such as residential solid fuel burning as well as biomass burning activities. Based on the national census data these activates are expected within low-income communities such as the one sampled in this study.

Even though these settlements are low-income, there is still a significant amount of traffic moving in and around these communities. KwaDela, for instance, is situated in a rural region next to the N17. This national carries a lot of transport (both vehicles and larger transport trucks) moving between the coastal and interior regions of South Africa. Similarly, KwaZamokuhle is also situated close to a nations (N11) and

regional (R38) routes. Jouberton is situated next to the N12 national route in an urbanised area. Despite the presence of the national road, the settlement carries a lot of traffic moving between the households. The movement of traffic in close proximity to the household leads to the resuspension of dust associated with both paved-and unpaved roads. Agincourt does not have any major traffic routes close by, however, it had numerous secondary routes most of which are unpaved. Traffic within these villages are associated more with transportation to and from work and schools. The villages surrounding Giyani are impacted by regional routes such as the R81 and R578, which are used to access the greater Giyani settlement. Similarly, the roads situated between the households are unpaved.

Based on the literature review on indoor source apportionment *(see Section 1.2.2.4, Table 1.6)* it is clear that there are multiple sources contributing to air pollution within the indoor environment. Road traffic and vehicle related emissions were identified in twenty-two (22) of the thirty-nine (39) studies reviewed. These included the USA *(Anderson et al., 2002; Hasheminassab et al., 2014; Hopke et al., 2003; Martuzevicius et al., 2008; Tunno et al., 2016; Yakovleva et al., 1999; Zhao et al., 2006, , 2007)*, India *(Gadkari & Pervez, 2007, , 2008; Kalaiarasan et al., 2017; Pervez et al., 2012)*, Canada *(Bari et al., 2015; Kim et al., 2005)*, China *(Chen et al., 2017; Zhu et al., 2012)*, Spain *(Amato et al., 2014; Minguillón et al., 2012)*, Chile *(Barraza et al., 2014)*, Denmark *(Palmgren et al., 2003)*, Germany & Finland *(Yli-Tuomi et al., 2008)*, and Sweden *(Molnár et al., 2014)*. Thus, traffic related particulate pollution is often present in the indoor environment. These sources are usually in close proximity to where people live, work, and go to school. Regardless of the geographic region, vehicle- and traffic emissions will have an impact on indoor air where this is a source of transportation. In South Africa, especially within low-income communities, vehicles are a main source of transportation to get to work and school.

Factor two (2) and three (3) accounted for 26.43% and 8.59%, respectively. However, it was identified at crustal soil emissions as Si, Al, K, P, Ca, Mg, and Na had correlation coefficients >0.5. The EFs supports this as it was between 1 and 100. These emissions could result from crustal soil particles being naturally resuspended into the air by winds that move across surfaces that are not covered by vegetation. This is a typical occurrence within low-income residential settlement as most of the houses are surrounded by bare soil and not covered by grass or other vegetation. Some households, especially in the rural areas, practice subsistence farming in close proximity to the residences which could also contribute to the resuspension of dust, this is referred to as “agricultural soil”. Crustal soil elements could also be mechanically resuspended by vehicles travelling on paved- (settled dust) and unpaved roads. The main roads in these type of settlements tend to be paved, while smaller arterial roads situated between the households are unpaved. These resuspended particles then infiltrate into the indoor environment of the residences through an opening in the household structure. In addition, household cleaning activities such as sweeping and dusting could attribute to the resuspension of dust particles that have settled on surfaces within the house.

Crustal soil was present in the indoor environment as a source in twenty-eight (28) of the reviewed studies. These were geographical spread out across the world and included the USA *(Adgate et al., 1998; Habre et al., 2014; Hasheminassab et al., 2014; Larson et al., 2004; Tunno et al., 2016; Yakovleva et al., 1999; Zhao et al., 2006, , 2007)*, India *(Gadkari & Pervez, 2007, , 2008; Kalaiarasan et al., 2017; Pervez et al., 2012; Suryawanshi et al., 2016)*, China *(Chen et al., 2017; Zhang et al., 2014; Zhu et al., 2012)*, Finland *(Koistinen et al., 2004; Yli-Tuomi et al., 2008)*, Greece *(Gemenetzis et al., 2006; Saraga et al., 2010)*, Belgium *(Buczyńska et al., 2014)*, Canada *(Kim et al., 2005)*, Chile *(Barraza et al., 2014)*, Ghana *(Zhou et al., 2014)*, Korea *(Park et al., 2012)*, Malaysia *(Ali et al., 2017)*, Spain *(Amato et al., 2014)*, and Sweden *(Molnár et al., 2014)*. The contribution of the soil sources to indoor air ranges from as low as 1% to as high as 70%. The high variability in its contribution indicates that there are a lot of local variables impacting on presence and contribution. The crustal soil component within the indoor environment of low-income residential communities in South Africa fall within the ranges presented in literature.

Factor four (4) accounted for 7.22% of the variability and represents waste burning emission as Zn, Sn, Pb, Ti, and Cu had correlation coefficients >0.5. Similarly to Factor 1, these elements had high to extreme enrichment indicating anthropogenic sources. Open waste burning activities are often practiced due to a lack of waste-collection services within these low-income communities. This number fall within the contribution range of solid waste burning identified in Ghana and Gambia, where it made up between 0 and 12% of indoor $PM_{2.5}$ in residential households *(Zhou et al., 2014)*.

The qualitative source contributions to PM_4 within the residential indoor environment categorised by community, settlement, and season, are summarised in *Figure 4.37*, *Figure 4.37*, and *Figure 4.38*. These variations are explored further in the following sections.

4.1.2.5.1. Sources contributing to indoor PM_4 within the coal-burning communities

The main factors contributing to PM_4 loadings within the residential indoor environment of low-income coal-burning communities are present in *Figure D.2.a* and *b*. Based on the PCA, three main factors explain 78.94% of the variability associated with the elemental mass concentration. The first factor, which represents crustal soil emission (Na, Mg, Al, Si, P, S, K, Ca, Ti, and Fe), accounted for 38.57% of the variability. Factor two (2) was attributed to road traffic emission (Cl, V, Cr, Mn, Cu, Zn, and Ba), and explained 31.43% of the elemental variability. The last factor, namely solid fuel combustion (Ti and Pb), explained 8.93% of the variation.

Seasonal variation of source contributions to indoor PM_4 within the coal-burning communities

During summer *(Figure D.3.a and b)*, 85.04% of the variability is explained by three factors. Crustal soil- (Na, Mg, Al, Si, P, K, Ca, Ti, and Fe) and road traffic (Cl, C, Cr, Mn, Cu, Zn, and Ba) emission accounted for 46.27% and 29.94% of the variation. The third contributing source was identified as waste burning emission (Ti, Zn, and Pb), accounting for 8.83% of the variability. During winter *(Figure D.4.a and b)*, 82.84% of the variability was attributed to four main factors. Solid fuel burning- (Cl, V, Cr, Mn, Cu, Zn, Ba, and Pb) and crustal soil (Na, Mg, Al, Si, S, K, Ca, Ti, and Fe) emissions accounted for 43.91% and 26.31% of the variability. The road traffic- (Ti, Zn, and Pb) and waste burning (Br and Sn) emissions, respective, explained 7.04% and 5.58% of the variability.

The summer-to-winter ratios indicated that contribution of crustal soil-, road traffic-, and waste burning emissions were factors of 1.76, 4.25, and 1.58 higher in summer. Solid fuel burning emissions were more prevalent during the winter. This can be linked to the increased need for heating, due to very low temperatures *(see Chapter 5, Section 5.1.3)*.

Residential solid fuel combustion is definitely a major contributing source to the indoor PM_4 loading in the coal-burning communities. However, it should be noted that the contribution from coal combustion could be even higher if the carbonaceous species where quantified in the analysis. This is due to the high level of non-combusted carbon associated with inefficient residential burning.

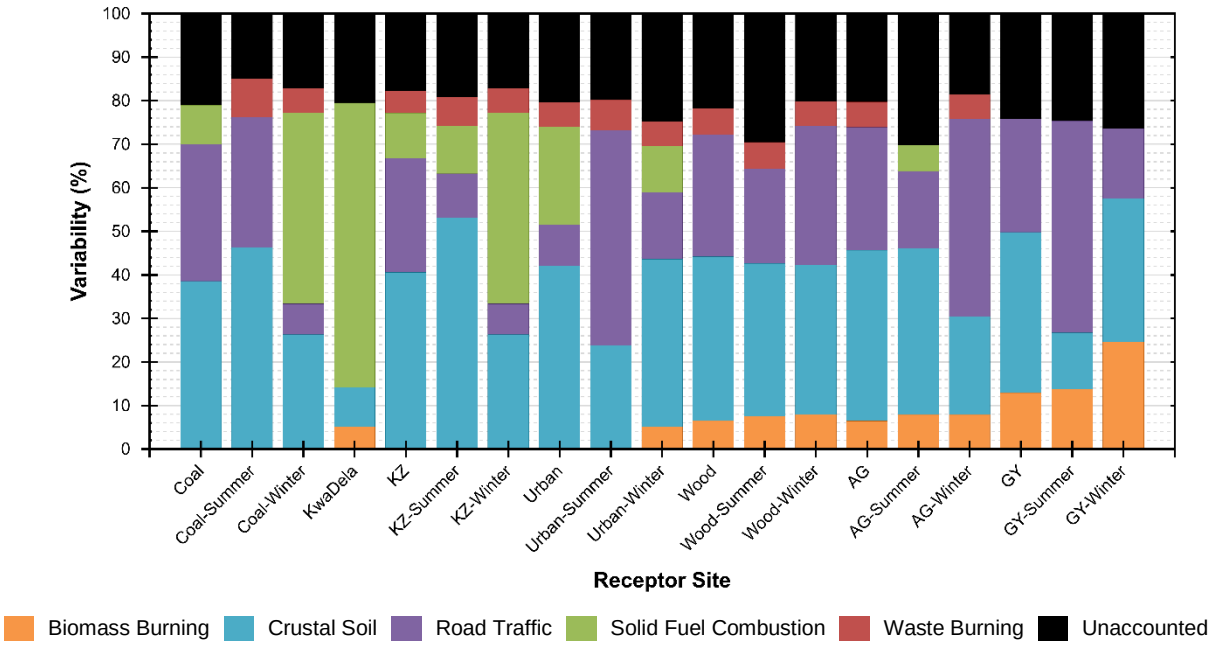

Figure 4.36 Stacked colum graph of the qualitative source contributions identified through the principal component analysis (PCA), categorised by community, settlement, and season. (***Note:*** KD – KwaDela, KZ – KwaZamokuhe, AG – Agincourt, GY – Giyani, S – Summer, and W – Winter)

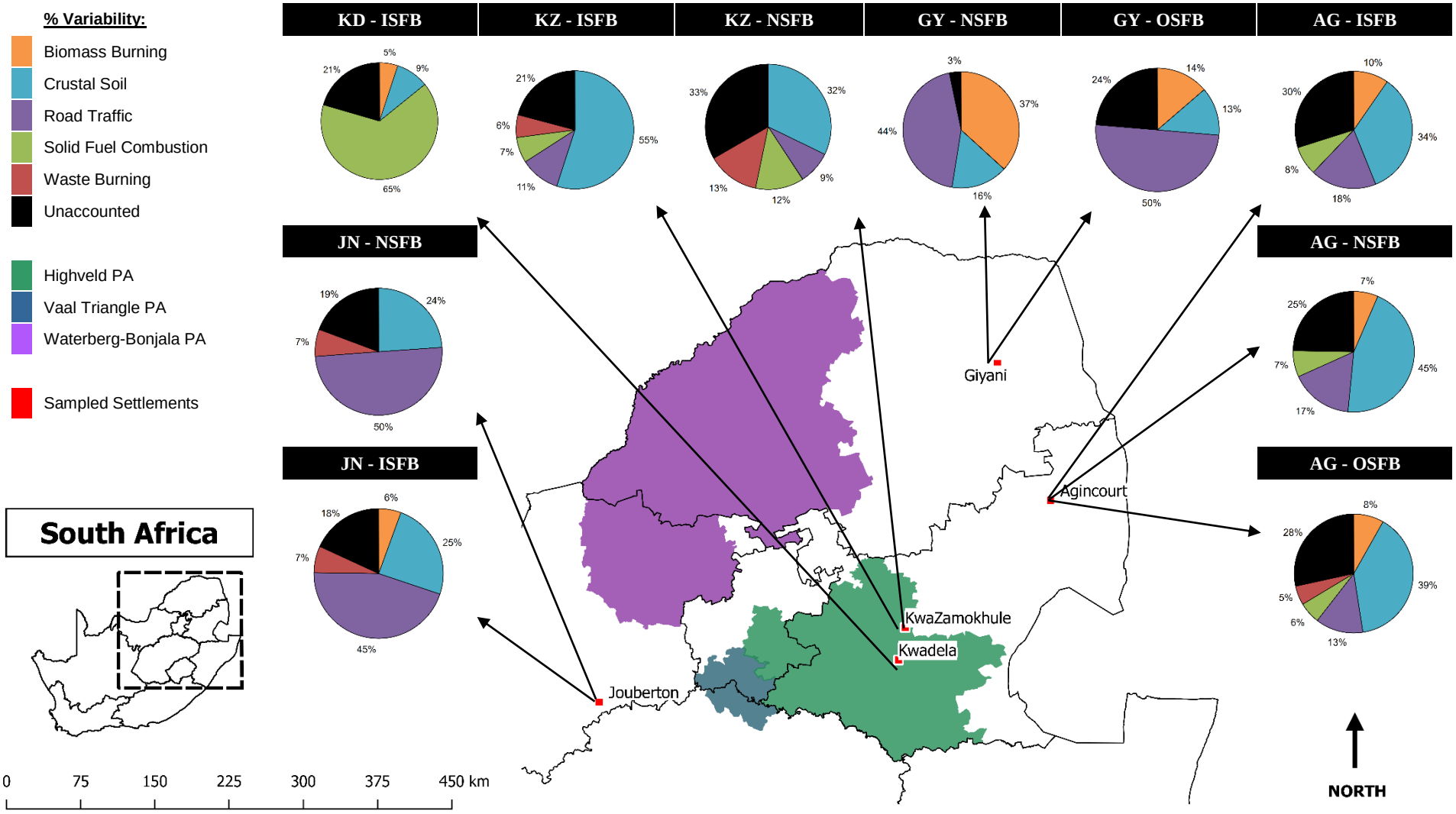

Figure 4.37 Summer PM_4 element mass cocntration variability explained (%), by PCA, within the residential indoor environment of ISFB-, NSFB-, and OSFB households in low-income settlements in South Africa.

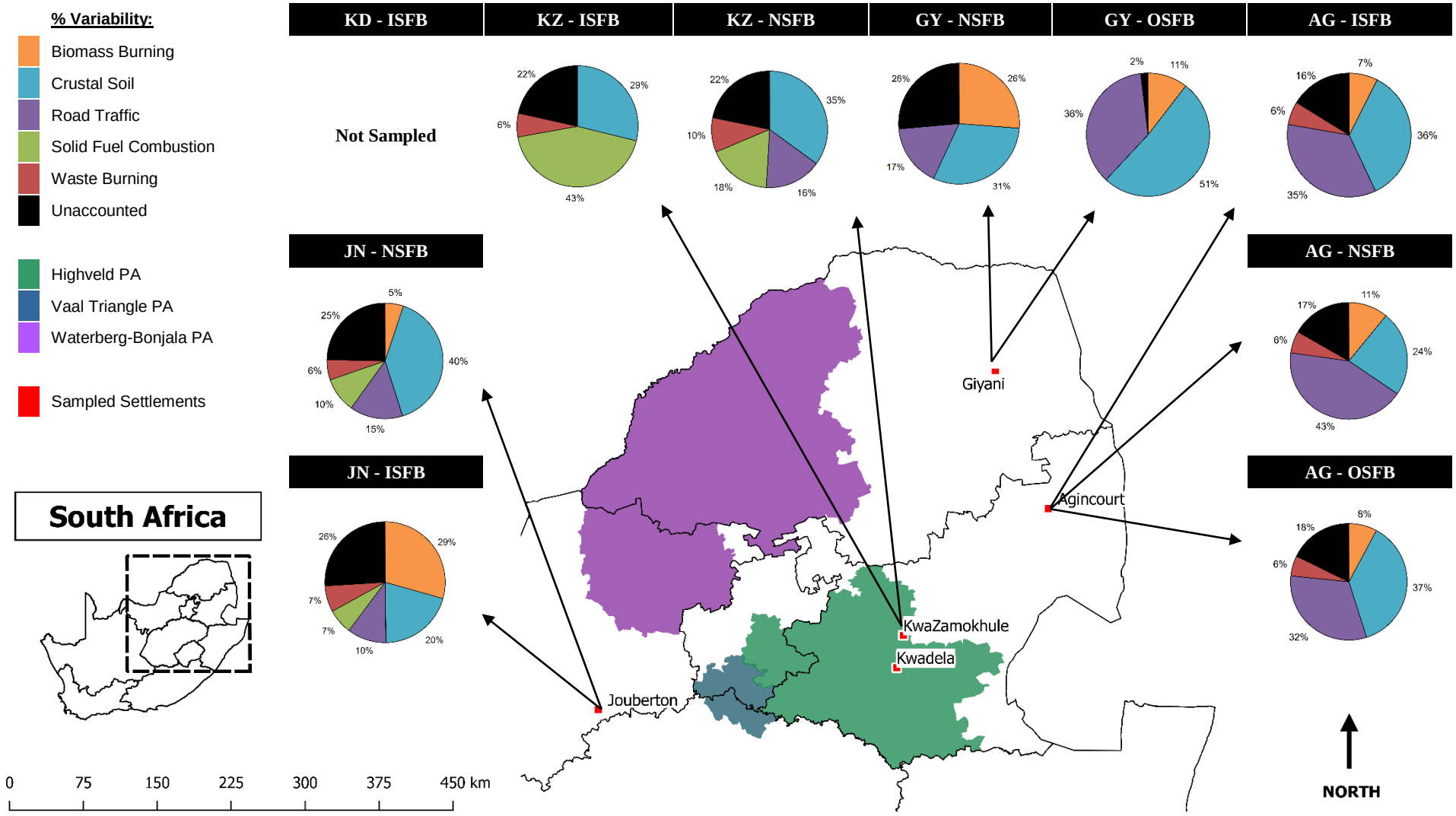

Figure 4.38 Winter PM_4 element mass cocntration variability explained (%), by PCA, within the residential indoor environment of ISFB-, NSFB-, and OSFB households in low-income settlements in South Africa.

Settlement variation of source contributions to indoor PM_4 within the coal-burning communities

In KwaDela (summer, ISFB) *(Figure D.5.a and b)*, three factors accounted for 79.48% of the variability. Solid fuel combustion- (Mg, P, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Cu, Zn, Ba, and Pb) and crustal soil (Na, Al, Si, and S) emissions explained 65.30 and 9.07% of the elemental variability. To a lesser degree, biomass combustion (K and Br) accounted for 5.11% of variability. The overall qualitative source contribution variability of 82.21%, in KwaZamokuhle *(Figure D.6.a and b)*, is explained by four factors. These factors include crustal soil- (Na, Mg, Al, Si, P, S, K, Ca, Ti, and Fe; 40.57%), road traffic- (Cl, V, Vr, Mn, Cu, Zn, and Ba; 26.24%), solid fuel combustion- (S, Ti, and Pb; 10.31%), and waste burning (Sn; 5.09%) emissions. During summer *(Figure D.7.a and b)*, 80.85% of the variability is explained by five factors. Crustal soil- (Na, Mg, Al, Si, P, Cl, K, Ca, Ti, Mn, and Fe) and road traffic (Cu, Zn and Pb) emissions accounted for 53.17% and 10.05% of the variation. The third contributing source was identified as waste burning (Br and Sn) emission, accounting for 6.61% of the variability. Both factor 4 (S and Cr) and 5 (Ba) were identified as originating from solid fuel combustion emissions (11.03%).

The summer KwaDela/KwaZamokuhle ratios indicated that the solid fuel combustion emissions were a factor of 5.92 times more prevalent in KwaDela, while crustal soil-, road traffic-, wand waste burning emission were more abundant in KwaZamokuhle.

Despite the fact that these two settlements are similar in many ways (geographic location, proximity to roads, climate, etc.), the contribution of specific sources are highly impacted by the activities which occur locally. In this case it showed that higher levels of solid fuel combustion were practiced within KwaDela during summer.

Household variation of source contributions to indoor PM_4 within the coal-burning communities

The qualitative source contributions to PM_4 within the residential indoor environment of the ISFB, NSFB, and OSFB households in the coal-burning communities, categorised by settlement, for summer and winter are given in *Figure 4.37* and *Figure 4.38*, respectively.

The summer source contribution in the ISFB dwellings for KwaDela was discussed above. In KwaZamokuhle, during summer, the ISFB *(Figure D.8.a and b)* and NSFB *(Figure D.9.a and b)* dwellings were dominated by crustal soil- (Na, Mg, Al, Si, P, Cl, K, Ca, Ti, Mn, and Fe; ***54.98%*** & Na, Mg, Al, Si, P, K, Ti, and Fe; ***32.27%***), road traffic- (Cu, Zn and Pb; ***10.92%*** and V and Br ***8.51%***), solid fuel combustion- (Br, Sn, and Ba; ***7.00%*** & Ti, Cu, and Pb; ***12.40%***), and waste burning (Cr and Sn; ***6.21%*** & S, Mn, & Sn; ***13.41%***) emissions. The summer ISFB/NSFB ratios for KwaZamokuhle indicated that biomass burning- and crustal soil emission were factors of 1.70 and 1.28 higher in the ISFB dwellings. Whereas, the solid fuel combustion- and waste burning emissions were higher in the NSFB households.

During winter, the ISFB *(Figure D.11.a and b)* and NSFB *(Figure D.12.a and b)* households were both influenced by crustal soil- (Na, Mg, Al, Si, P, S, K, Ca, Ti, and Fe; ***28.88%*** & Na, Mg, Al, P, S, Cl, K, and Ca; ***35.02%***), solid fuel combustion- (Na, Cl, V, Cu, Zn, Ba, and Pb; ***43.25%*** & Al, Si, Ti, V, Fe, S, Cr, and Ba; ***17.76%***), and waste burning (Zn and Sn; ***6.34%*** & Br and Sn; ***9.59%***) emissions. Road traffic emissions (Ti, Mn, Cu, Zn, and Pb; ***15.84%***) were only present within the NSFB houses. Most of the emissions were more prevalent in the NSFB dwellings with the exception of fuel combustion emission, which were higher (ratio: 2.44) within the ISFB houses.

The summer-to-winter ratios for the ISFB- and NSFB households in KwaZamokuhle indicated that waste burning emission were close to unity (ambient source), while solid fuel combustion emissions were higher during the winter. Crustal soil- and road traffic emissions were more prevalent in the summer.

4.1.2.5.2. Sources contributing to indoor PM_4 within the urban community

The main factors contributing to PM_4 loadings within the residential indoor environment of low-income urban community is present in *Figure D.13.a* and *b*. Based on the PCA, four main factors explain 79.64% of the variability associated with the elemental mass concentration. The first factor, which represents crustal soil (Na, Mg, Al, Si, P, Cl, K, Ca, Ti, and Fe) emission, accounted for 42.10% of the variability. Factor two (2) was attributed to solid fuel combustion (Ti, V, Cr, Mn, Cu, Ba, and Pb) emission, and explained 22.52% of the elemental variability. The third factor was identified as road traffic (Cu, Zn, and Sn) emission, which explained 9.43% of the variability. The last factor, namely waste burning (Fe and Br), explained 5.59% of the variation.

Season variation of source contributions to indoor PM_4 within the urban community

During summer *(Figure D.14.a and b)*, 80.17% of the variability is explained by three factors. Road traffic- (Cl, Ti, V, Cr, Mn, Fe, and Cu) and crustal soil (Na, Mg, Al, Si, P, K, Ca, Ti, and Fe) emissions accounted for 49.42% and 23.79% of the variation. The third contributing source was identified as waste burning (Zn and Sn) emission, accounting for 6.96% of the variability.

During winter *(Figure D.15.a and b)*, 74.30% of the variability was attributed to five factors. Crustal soil- (Na, Mg, Al, Si, P, Cl, and K) and road traffic (Cu and Zn) emissions accounted for 38.48% and 14.50% of the variability. The solid fuel- (Al, Si, Ti, V, Mn, and Fe) and waste burning (Cr) emissions, respective, explained 10.58% and 5.64% of the variability. The final factor, namely biomass burning (Br) explained 5.10% of the elemental variability.

The summer-to-winter ratios indicated that contribution of biomass burning-, crustal soil-, and solid fuel combustion emissions were higher during winter. Road traffic- (3.21) and waste burning (1.23) emission emissions were more prevalent during the summer.

The urban community of Jouberton is not considered to be a residential solid fuel burning community making it a surprising contributor to indoor PM_4, during winter. Similarly, the high level of biomass burning emission were also not expected.

Household variation of source contributions to indoor PM_4 within the urban community

The qualitative source contributions to PM_4 within the residential indoor environment of the ISFB, NSFB, and OSFB households in the urban community, categorised by settlement, for summer and winter are given in *Figure 4.37* and *Figure 4.38*, respectively.

In Jouberton, during summer, the ISFB *(Figure D.15.a and b)* and NSFB *(Figure D.16.a and b)* dwellings were dominated by crustal soil- (Mg, Al, Si, P, S, K, Ca, and Fe; ***24.52%*** & Na, Mg, Al, Si, P, K, Ca, Ti, and Fe; ***23.90%***), road traffic- (Na, Cl, Ti, V, Cr, Mn, Fe, Cu, Ba and Pb; ***45.04%*** & Cl, Ti, V, Cr, Mn, Cu, Zn, Ba, and Pb; ***49.87%***), and waste burning (Zn and Sn; ***6.65%*** & Zn and Sn; ***6.90%***) emissions. The biomass burning (Br; ***5.62%***) emissions were only identified for the ISFB houses. The summer ISFB/NSFB ratios for Jouberton indicated that all the emission, with the exception of biomass burning, was close to unity.

During winter, the ISFB *(Figure D.18.a and b)* and NSFB *(Figure D.19.a and b)* households were both influenced by biomass burning- (Na, Mg, P, Cl, K, and Ca; ***29.41%*** & Br; ***5.16%***), crustal soil- (Al, Si, S, Ti, Mn, and Fe; ***20.35%*** & Na, Mg, Al, Si, P, Cl, K, and Ca; ***39.92%***), road traffic- (Cu and Zn; ***10.43%*** & Cu, Zn , and Sn; ***14.73%***), solid fuel combustion- (S, Cr, Br, and Sn; ***6.77%*** & Si, Ti, V, Mn, and Fe; ***9.81%***), and waste burning (Sn and Ba; ***7.02%*** & Cr; ***5.69%***) emissions. The ISFB dwellings had higher contributions from biomass burning- (ratio: 5.70) and waste burning (ratio: 1.23) emissions. The NSFB houses, on the other hand, showed higher abundance of crustal soil-, road traffic-, and combustion emissions.

The summer-to-winter ratios for the ISFB household in Jouberton indicated that waste burning emission were close to unity, while crustal soil- (ratio: 1.20) and road traffic (ratio: 4.32) emissions were higher during the summer. Biomass burning- and solid fuel combustion emissions were more prevalent in the summer. For the NSFB dwellings, road traffic- (ratio: 3.39) and waste burning (ratio: 1.21) emissions had higher levels of abundance during summer. While biomass burning-, crustal soil-, and solid fuel combustion emissions were more prevalent in the winter.

Emission resulting from the combustions of solid fuels, such as coal and wood, were more prevalent during the winter within the ISFB-and NSFB dwellings of the urban low-income settlement. Waste burning emissions, mainly originate in the ambient environment and appear to be a constant source across all seasons.

4.1.2.5.3. Sources contributing to indoor PM_4 within the wood-burning communities

The main factors contributing to PM_4 loadings within the residential indoor environment of low-income wood-burning communities are present in *Figure D.20.a* and *b*. Based on the PCA, five main factors explain 78.16% of the variability associated with the elemental mass concentration. The first factor, which represents crustal soil (Mg, Al, Si, P, S, K, Ca, and Ti) emission, accounted for 37.70% of the variability. Factors two (Ti, V, Cu, Ba, and Pb) and three (Cr and Fe) were attributed to road traffic emission, and explained 28.08% of the elemental variability. Factor four was identified as biomass burning (Na and Cl), accounting for 6.48% of the elemental variability. The last factor, namely waste burning (Zn and Sn), explained 5.91% of the variation.

Season variation of source contributions to indoor PM_4 within the wood-burning communities

During summer *(Figure D.21.a and b)*, 70.49% of the variability is explained by three factors. Crustal soil- (Mg, Al, Si, P, K, Ca, Ti, and Mn) and road traffic (Cr, Me, Cu, and Zn) emissions accounted for 35.00% and 21.76% of the variation. The third contributing source was identified as biomass burning (Na, Mg, and Cl) emission, accounting for 7.59% of the variability. The final factor, namely waste burning (Sn and Pb), explained 6.12% of the elemental variability.

During winter *(Figure D.22.a and b)*, 79.84% of the variability was attributed to four main factors. Crustal soil- (Mg, Al, Si, P, S, K, Ca, and Ti) and road traffic (Ti, V, Cr, Mn, Fe, Cu, Zn, Ba, and Pb) emission accounted for 34.39% and 31.93% of the variation. The third contributing source was identified as biomass burning (Na and Cl) emission, accounting for 7.94% of the variability. The final factor, namely waste burning (Zn and Sn), explained 5.58% of the elemental variability.

The summer-to-winter ratios show that contribution of road traffic emission were more abundant during winter. All the other emission sources were close to unity. This indicates that the sources contributing to the indoor PM_4 is relatively constants at the community level, lending support to the assumption that most of the sources have an ambient origin in the wood burning communities.

Settlement variation of source contributions to indoor PM_4 within the wood-burning communities

The overall qualitative source contribution variability of 79.73%, in Agincourt *(Figure D.23.a and b)*, is explained by four factors. These factors include crustal soil- (Mg, Al, Si, P, S, K, Ca, and Ti; ***39.18%***), road traffic- (Ti, V, Cr, Mn, Fe, Cu, Ba, and Pb; ***28.29%***), biomass burning- (Na and Cl; ***6.43%***), and waste burning (Zn and Sn; ***5.83%***) emissions. During summer *(Figure D.24.a and b)*, 69.74% of the variability is explained by five factors. Crustal soil- (Mg, Al, Si, P, K, Ca, Ti, Mn, and Fe) and road traffic (Cr, Fe, Cu, and Zn) emission accounted for 38.21% and 17.75% of the variation. The biomass burning (Na, Mg, and Cl) emission, accounted for 7.87% of the variability, while the solid fuel burning (Cr and Fe) emission

explained 5.91%. During winter *(Figure D.28.a and b)*, 81.39% of the variability was explained by similar emissions. Road traffic- (Ti, V, Cr, Mn, Fe, Cu, Ba, and Pb) and crustal soil (Al, Si, P, S, K, Ca, and Ti) emission accounted for 41.07% and 22.57% of the variation. The biomass burning (Na and Cl) emission accounts for 7.88% of the variability. The waste burning (Zn and Sn) emission explained only 5.63%.

The overall qualitative source contribution variability of 75.78%, in Giyani *(Figure D.32.a and b)*, is explained by five factors that were grouped into three emission sources. These factors include crustal soil- (Na, Mg, Al, Si, P, S, K, Ca, Ti, and Mn; ***36.89%***), road traffic- (Cr, Fem Cu, Zn, and Pb; ***25.99%***), and biomass burning (Na, Cl, Br, Sn, and Ba; ***12.89%***) emissions. During summer *(Figure D.33.a and b)*, 75.34% of the variability was accounted for. The road traffic- (Ti, Cr, Fe, Cu, and Zn), biomass burning- (Na, Cl, Mn and Br), and crustal soil (Mg, Al, Si, P, S, K, and Ca) emissions accounted for 48.63%, 13.83, and 12.89% of the variation. During winter *(Figure D.36.a and b)*, 73.55% of the variability was accounted for by crustal soil- (Al, So, K, Ti, Mn, and Fe; ***33.03%***), road traffic- (V, Cu, Zn, and Pb; ***15.95%***), and biomass burning (P and Ca; ***24.58%***) emissions.

The mean Agincourt/Giyani ratios indicated that the biomass burning emissions were more prevalent in Giyani, while waste burning emissions were more abundant in Agincourt. During the summer, both the crustal soil- and solid fuel combustion emissions were more abundant in Agincourt compared to Giyani. Also, crustal soil and waste burning emission were more abundant in Agincourt during winter, compared to Giyani. In Giyani, road traffic emission accounted for a larger percentage of the variability during summer, while for winter it was biomass burning.

All the wood-burning settlements showed biomass combustion as a contributing source. This highlights the fact that communities within the Lowveld-region are reliant of wood-burning as a primary source of energy. Biomass burning is not identified as the dominant source, but does have a discernable impact on the level of indoor PM_4 within the residential household in these settlements.

Household variation of source contributions to indoor PM_4 within the wood-burning communities

The qualitative source contributions to PM_4 within the residential indoor environment of the ISFB, NSFB, and OSFB households in the wood-burning communities, categorised by settlement, for summer and winter are given in *Figure 4.37* and *Figure 4.38*, respectively.

In Agincourt, during summer, the ISFB *(Figure D.25.a and b)*, NSFB *(Figure D.26.a and b)*, and OSFB *(Figure D.27.a and b)* dwellings were dominated by biomass burning- (9.68, 6.51, and 8.20%), crustal soil- (34.20, 45.01, and 39.33%), road traffic- (18.21, 16.70, and 12.95%), and solid fuel combustion- (7.99, 7.03, and 5.87%) emissions. Waste burning (5.20%) emissions were only identified within the OSFB houses. The summer ISFB/NSFB and ISFB/OSFB ratios for Agincourt indicated that the biomass burning-

, crustal soil-, and solid fuel combustion emissions were more prevalent in the ISFB dwelling. Crustal soil- and waste burning emissions had higher levels of abundance within the NSFB and OSFB dwellings.

During winter, in Agincourt, the ISFB *(Figure D.29.a and b)*, NSFB *(Figure D.30.a and b)*, and OSFB *(Figure D.31.a and b)* households were both influenced by biomass burning- (7.49, 10.93, and 7.88%), crustal soil- (35.50, 23.56, and 37.17%), road traffic- (34.73, 42.69, and 31.57%), and waste burning (6.06, 6.08, and 5.62%) emissions. The winter ISFB/NSFB ratios showed higher abundance of crustal soil (ratio: 1.51) emissions within the ISFB houses. The biomass burning- and road traffic emission had higher abundance within the NSFB houses. The ISFB/OSFB ratios were all close to unity. The NSFB/OSFB ratios showed that both the biomass burning- (ratio: 1.39) and road traffic (ratio: 1.35) emission were more prevalent in the OSFB households, while crustal soil emissions were higher within the NSFB.

The summer-to-winter ratios, in Agincourt, for the ISFB dwellings had higher contributions from biomass burning- (ratio: 1.29) emissions during summer, while road traffic- and waste burning emission were more abundant during the winter. Crustal soil was close to unity. The NSFB houses, on the other hand, showed higher abundance of crustal soil (ratio: 1.91) emission during summer. The winter had higher abundance of biomass burning-, road traffic- and waste burning emissions. Within the OSFB dwelling road traffic emission were more prevalent during winter. The remaining source emission categories were close to unity.

Road traffic emissions were the most abundant source contributing to PM loadings during winter in all three household types (ISFB, NSFB, and OSFB). Crustal soil and biomass burning emission were also found to make an important contribution. The biomass and waste burning sources were close to unity indicating that these originate within the ambient environment, and affect all household in the community in a similar way.

In Giyani, during summer, the NSFB *(Figure D.34.a and b)* and OSFB *(Figure D.35.a and b)* dwellings were dominated by biomass burning- (36.76 and 13.70%), crustal soil- (15.70 and 12.71%), and road traffic (44.27 and 49.89%) emissions. The summer NSFB/OSFB ratios for Giyani indicated that the biomass burning- (ratio: 2.68) and crustal soil (ratio: 1.24) were more abundant within the ISFB dwellings, while road traffic emission were prevalent in the OSFB households.

During winter, the NSFB *(Figure D.37.a and b)* and OSFB *(Figure D.38.a and b)* households were both influenced by biomass burning- (26.20 and 10.50%), crustal soil- (30.66 and 51.39%), and road traffic- (16.70 and 36.17%) emissions. The ISFB dwellings had higher contributions from biomass burning- (ratio: 2.50) emissions. The NSFB houses, on the other hand, showed higher abundance of crustal soil- and road traffic emissions.

The summer-to-winter ratios for the ISFB and OSFB household in Giyani indicated that waste burning- (ratio: 1.40 and 1.30) and road traffic (ratio: 2.65 and 1.38) related emissions were higher during the

summer. Crustal soil emissions within the ISFB and OSFB were more abundant during winter. The higher abundance of crustal soil emissions is almost certainly a result of poor vegetative cover and low rainfall during winter with the Giyani region.

The crustal soil-, road traffic-, solid fuel combustion-, waste-, and biomass burning- emission, identified for the residential indoor environments, show variation in its contribution to indoor PM_4 with the five settlements sample in this study. The study was able to confirm that the indoor environment within each of the three community types were impacted by solid fuel burning within the coal-burning communities; road traffic and crustal soil within the urbanised community; and biomass combustion in the wood-burning communities. The qualitative contribution is very much dependent on the actual element mass concentrations, associated crustal enrichment, and element-to-element relationships. All of which are impacted by the activities practices by residents within and around the settlements as well as the local meteorological condition.

This is a first attempt to identify and quantify the sources contributing to the indoor environment of various low-income residential settlements, in varying geographic regions, in South Africa. The finding from this study informs emerging knowledge surrounding residential indoor air quality in South Africa. The study suggest that each individual household is a receptor in its own right. In addition it showed that similar communities within a small geographic region have high variations in its indoor pollutant concentrations, thus the generalisation of single household indoor particulate data should be done with care. The study provides a good baseline for indoor particulate pollution, which could inform future work related to indoor air quality guidelines and standards as well as exposure and health.

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This chapter addressed the results and discussions surrounding Objective II and III, as outlined in *Chapter 1 Section 1.4*. , which focused on the spatial and temporal characterisation of residential indoor continuous- and gravimetric PM_4 mass concentrations, associated trace elements, and possible contributing sources. The residential indoor PM_4 measurements were characterised based on its mass concentrations, diurnal patters, day-night variations, and the 24-hr PM2.5 exceedances of the NAAQS and WHO guidelines. The indoor environment was subject to high PM_4 loading showing a distinct bi-modal diurnal pattern. The morning- and evening peaks correspond to times of increased residential combustion- and road traffic activities. The indoor $PM_{2.5}$ exceed both the NAAQS and WHO on a regular bases indicating constant exposure to hazardous particulate loadings. The qualitative source contributions were calculated based on the element abundance, enrichment factors, and correlation coefficients. The five main source categories contribution to indoor PM_4 was crustal

soil-, road traffic-, solid fuel combustion-, waste burning- and biomass burning emissions. The following chapter addresses the characterisation of the local meteorological conditions and its association with the indoor PM_4 loadings.

CHAPTER 5: METEOROLOGY OF THE STUDY AREA

This chapter aims to address the results and discussion surrounding Objective IV, as outlined in *Chapter 1 Section 1.4*. In order to assess indoor air pollution and composition accurately, it is important and necessary to understand the general climate of the region as well as the diurnal and seasonal variations of the synoptics circulation and its impacts on the local meteorology. The purpose of this chapter is to provide an overview of the observed synoptic and local meteorological conditions that occurred over KwaDela, KwaZamokuhle, Jouberton, Agincourt, and Giyani. The conditions are compared to the climatic conditions for the period 1981 to 2010, as described in *Chapter 1, Section 2.2*. As well as investigate the relationship that exists between the observed synoptic circulations, local meteorology and indoor PM_4 mass concentrations.

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The rationale for investigating the possible association between observed synoptics and indoor particulate pollution is found within its potential to directly or indirectly impact particulate concentrations. Directly the synoptic circulation will impact energy use and in turn influence emissions. However, the indirect links are more complex and includes:

(i) synoptic conditions influences the stability of the atmosphere which impacts on the ambient air quality and in turn indoor air pollution levels thought aspects such as infiltration.
(ii) synoptic conditions impacts the social behaviour of people, which impacts on the ambient air quality and in turn indoor air pollution.
(iii) synoptic conditions influences emission which impacts on the ambient air quality and in turn indoor air pollution levels.

5.1. Observed meteorological conditions

5.1.1. Regional synoptic-scale circulation

The monthly frequency of occurrence, as a percentage of total observation, for the various synoptic circulation patterns are presented in *Figure 5.1* below. A total of 927 observations were made from 2 July 2013 to 20 November 2017. These observations only included the days of active sampling during each of the twenty-one (21) sampling campaigns *(see Table 2.2)*. January and December were thus excluded from the analysis. There were eight (8) days (0.86%) for which synoptic charts were unavailable.

The most dominant synoptic-scale circulation conditions *(Figure 5.1)* were that of the continental anticyclones (43.32%) followed by the easterly waves (27.59%), ridging anticyclones (13.79%), cut-off lows (9.48%), and westerly waves (3.34%). The remainder of the synoptic circulation patterns, namely the coastal lows, easterly lows, southerly meridional flow, west-coast troughs, and cold snaps each occurred in less than 1.00% of the observations.

Observation made during the study period *(Figure 5.1)* indicates similar occurrence of continental anticyclones, to that of the historical data *(Figure 1.4.k)*. The highest occurrence was during the winter period (range: 45.29% to 62.76%) and lowest during late summer (25.41%). This is also true for easterly waves with the highest occurrence in February (59.02%) and lowest in winter months, ranging between 6.21 and 14.12%. The ridging anticyclones differs slightly from the historical trend as the maximum peak was observed during mid-winter (22.35%) with a smaller peak in early autumn (15.13%). The lowest frequencies occurred in mid- to late-spring with 6.45% and 6.52%, respectively. The westerly wave frequencies ranged between zero and 11.67% with the maximum occurring during June. Cut-off low conditions were consistent with the historical representation, as the highest prevalence was during spring (9.68% to 15.22%) and lowest in late- summer (4.10%). The first peak (early-autumn to early-winter) was not pronounced in the observed data and presents as a gradual increase toward spring.

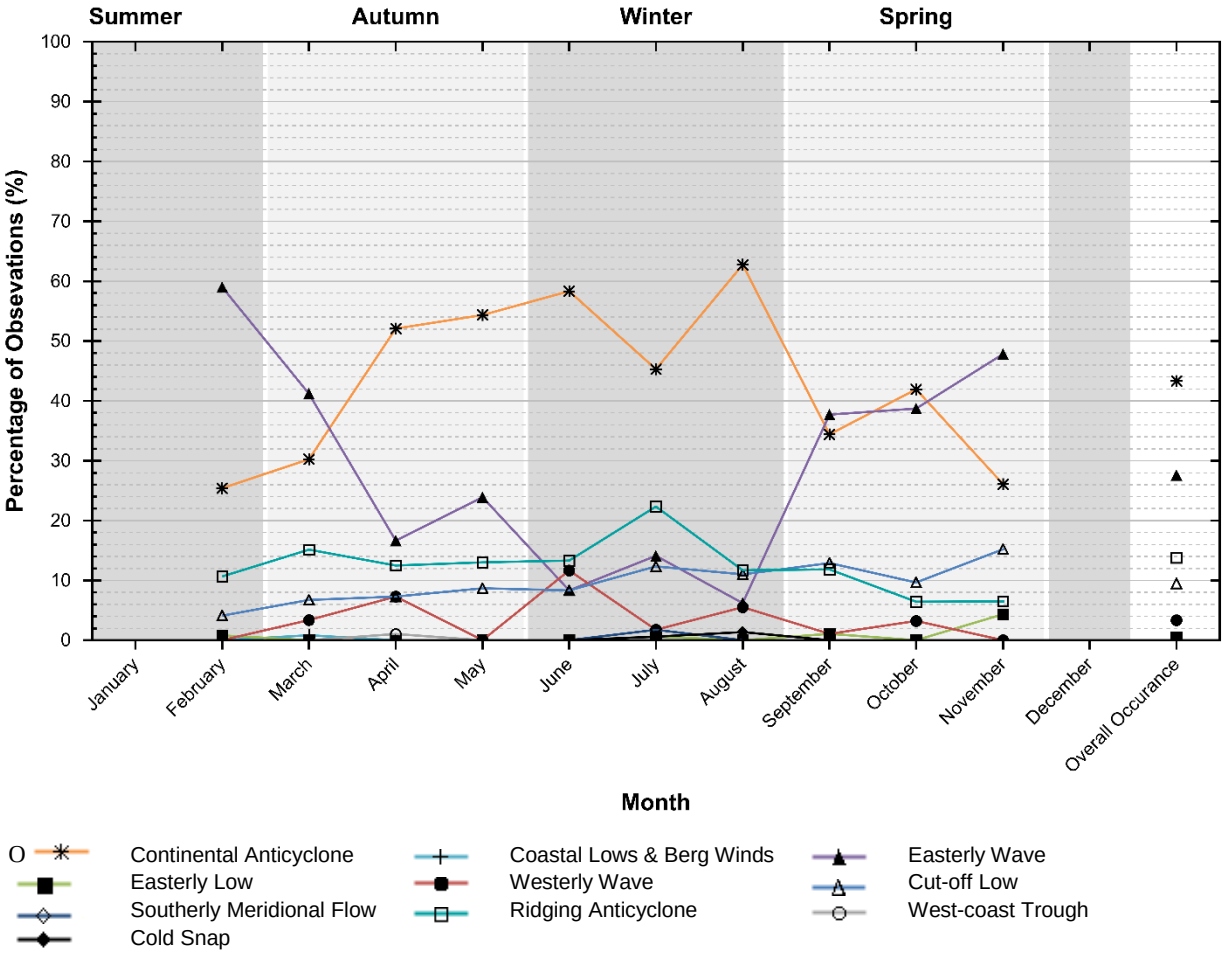


Figure 5.1 The frequency of occurrence (percentage) for synoptic circulation conditions observed during all 21 sampling campaigns conducted between 2013 and 2017. (*Note:* no sampling took place during January and December).

Having discussed the main synoptic-scale circulations, the impact of each will be discussed for the twenty-one (21) sampling campaigns conducted during this study in terms of their frequency of occurrence and the duration for which it prevails.

5.1.1.1. Regional synoptic-scale circulation over the Highveld region

5.1.1.1.1. Spring

A single spring campaign was conducted in the Highveld region during the study period. It was undertaken in KwaZamokuhle from 2 September to 26 November 2015 (Campaign no.6 – *see Table 2.2*). This region was dominated by anticyclonic conditions which prevailed more than half of the sampling period *(Figure 5.2.a)*. The continental anticyclonic flow was present in 43.02% of the observations, easterly waves (33.72%), cut-off lows (15.12%) and ridging anticyclones (6.98%). The continental anticyclones and easterly waves lasted between twenty-four (24) and seventy-two (72) hours *(Figure 5.2.g)*. However, during the three months, there were four (4) and three (3) occasions, respectively, where the aforementioned persisted for four (4) consecutive days (~96 hours).

5.1.1.1.2. Summer

A total of six (6) summer campaigns were conducted in the Highveld region during the study period. This included two (2) campaigns in each of the settlements, namely KwaDela, KwaZamokuhle and Jouberton (Campaign no. 2, 4, 7, 10, 11, and 13 – *see Table 2.2*). Majority of the sampling occurred between early February and late May, with the exception of campaign ten (10) which was done during the month of November. Similarly to the springtime, the summer was dominated by anticyclonic flow (range: 48.84% to 58.93%) in four (4) of the campaigns (no. 2, 4, 7, and 11) *(Figure 5.2.a)*. However, during campaign ten (10) and thirteen (13) easterly flow prevailed for more than seventy (70) per cent of the sampled days. Both of these campaigns were conducted in 2017.

The 2014 *(Figure 5.2.c)* campaign undertaken in KwaDela lasted almost three (3) months. The majority of the anticyclones continued for periods ranging between twenty-four (24) to forty-eight (48) hours, however, there was one instance where the continental anticyclone persisted for nine (9) days (2014/04/06 to 2014/04/14). These conditions were often interrupted by easterly flow lasting anywhere between twenty-four (24) and ninety-six (96) hours. On seven (7) occasions, the above mentioned were disturbed by the presence of a cut-off low-pressure system, never lasting longer than two (2) days. The 2015 period *(Figure 5.2.e)* showed similar trends to 2014.

In KwaZamokuhle during the 2016 campaign *(Figure 5.2.h)*, lasting approximately two (2) months, anticyclone conditions lasted twenty-four (24) to forty-eight (48) hours on fourteen (14) of the sixteen (16) instances. Toward the end of the sampling period, there was one (1) instance in which the conditions persisted for ten (10) days, between 2016/04/06 and 2016/04/15. The anticyclonic conditions were disturbed by the intrusion of easterly flow, and westerly disturbances (westerly waves and cut-off lows). The easterly flows persisting for periods of up to four (4) days and the latter never longer than twenty-four (24) hours. The 2017 sampling campaign *(Figure 5.2.k)*, lasted for a much shorter period of only three (3) weeks. Easterly flow dominated (as previously mentioned) and was sporadically interrupted by short (one to two days) incursions of anticyclones. The longest uninterrupted period of easterly flow lasted approximately eleven days, from 2017/11/08 to 2017/11/18.

Jouberton is situated more toward the interior of South Africa, and thus it is expected that condition will differ from those experienced in KwaDela and KwaZamokuhle to the east. During the 2016 campaign *(Figure 5.2.l)* there was a constant rotation in the occurrence of anticyclones (continental and ridging) and easterly flow. The majority (thirteen instances) of the anticyclone flow lasted for a period of twenty-four (24) to forty-eight (48) hours. On a single occasion (2016/05/15 to 2016/05/18) the conditions persisted for over four days (approximately ninety-six hours). The easterly flow dominated for five (5) consecutive days from 2016/04/16 to 2016/04/20, while all other incidences lasted between twenty-four (24) to seventy-two (72) hours. However, there is a significant difference between the 2016 and 2017 sampling periods. In 2017 *(Figure 5.2.n)* easterly flow dominated (similar to KwaZamokuhle during 2017. The longest uninterrupted period of easterly flow lasted approximately nineteen days (2017/02/01 to 2017/02/19).

5.1.1.1.3. Winter

Seven (7) winter campaigns were conducted in the Highveld region during the study period. This included two (2) campaigns each in KwaDela and Jouberton (Campaign no. 1, 3, 12, and 14 – *see Table 2.2*). Three (3) campaigns were conducted in KwaZamokuhle (Campaign no. 5, 8, and 9 – *see Table 2.2*). Most of the sampling occurred between July and September. The anticyclonic flow was more prevalent during the winter (range: 54.55% to 77.78%) compared to spring and summer *(Figure 5.2.a)*.

Both the 2013- *(Figure 5.2.b)* and 2014 *(Figure 5.2.d)* sampling campaigns carry out in KwaDela covered a period of about two (2) months. The continental anticyclones continue to persist for periods ranging from twenty-four (24) to forty-eight (48) hours, however, there were increased instances in which the anticyclonic conditions persevered longer than five (5) days. The longest was a twelve (12) day event, from 2013/07/05 to 2017/07/16. The conditions were often disturbed by the intrusion of easterly- and westerly flows, never lasting more than forty-eight (48) hours.

The KwaZamokuhle 2015 *(Figure 5.2.f)* and 2017 *(Figure 5.2.j)* campaigns covered a shorter sampling period of two- (2) to three (3) weeks, while the 2016 *(Figure 5.2.i)* sampling period lasted about two (2) months. The frequency of occurrence for anticyclonic-, easterly-, and westerly flows was similar across the three sampling periods.

The anticyclonic conditions persisted for shorter periods (one to four days) during 2015 and 2017, while during 2016 there was one instance in which it prevailed for ten (10) days, from 2016/08/04 to 2016/08/13. The conditions were often interrupted by similar intrusions as experienced in KwaDela, however, during 2016 there were two periods where other than anticyclonic conditions prevailed for a period a four- (2016/07/20 to 2016/07/23) and seven (2016/09/02 to 2016/09/08) days. The first was characterised by westerly disturbances (cut-off lows) and the second by easterly waves.

The two winter sampling periods in Jouberton during 2016 *(Figure 5.2.m)* and 2017 *(Figure 5.2.o)* were approximately five (5) weeks in length. Anticyclonic conditions (continental and ridging) persisted for more than seventy (70) per cent of the observed days, lasting for periods as short as twenty-four (24) hours and as long as twelve (12) days. These conditions were periodically interrupted by mainly easterly flow in 2016 and westerly disturbances during 2017.

5.1.1.2. Regional synoptic-scale circulation over the Lowveld region

5.1.1.2.1. Spring

A single spring campaign was conducted in the Lowveld region during the study period. It was undertaken in Giyani from 6 September to 15 September 2016 (Campaign no.19 – *see Table 2.2*). This region was dominated by easterly flow which prevailed for more than seventy (70) per cent of the sampling period *(Figure 5.2.a)*. These conditions persisted on average for forty-eight (48) to seventy-two (72) hours *(Figure 5.2.t)*, often being disturbed by continental anticyclones lasting for shorter periods of approximately twenty-four (24) hours.

5.1.1.2.2. Summer

A total of three (3) summer campaigns were conducted in the Lowveld region during the study period. This included two (2) campaigns in Agincourt and a single campaign in Giyani (Campaign no. 15, 17 and 20 – *see Table 2.2*). The sampling was done between early February and late May. The two sampling periods in Agincourt, conducted in 2016 *(Figure 5.2.p)* and 2017 *(Figure 5.2.r)*, were approximately five (5) weeks in length (same period as for Jouberton), while the summer campaign was undertaken in Giyani *(Figure 5.2.u)* lasted for a period of four (4) weeks.

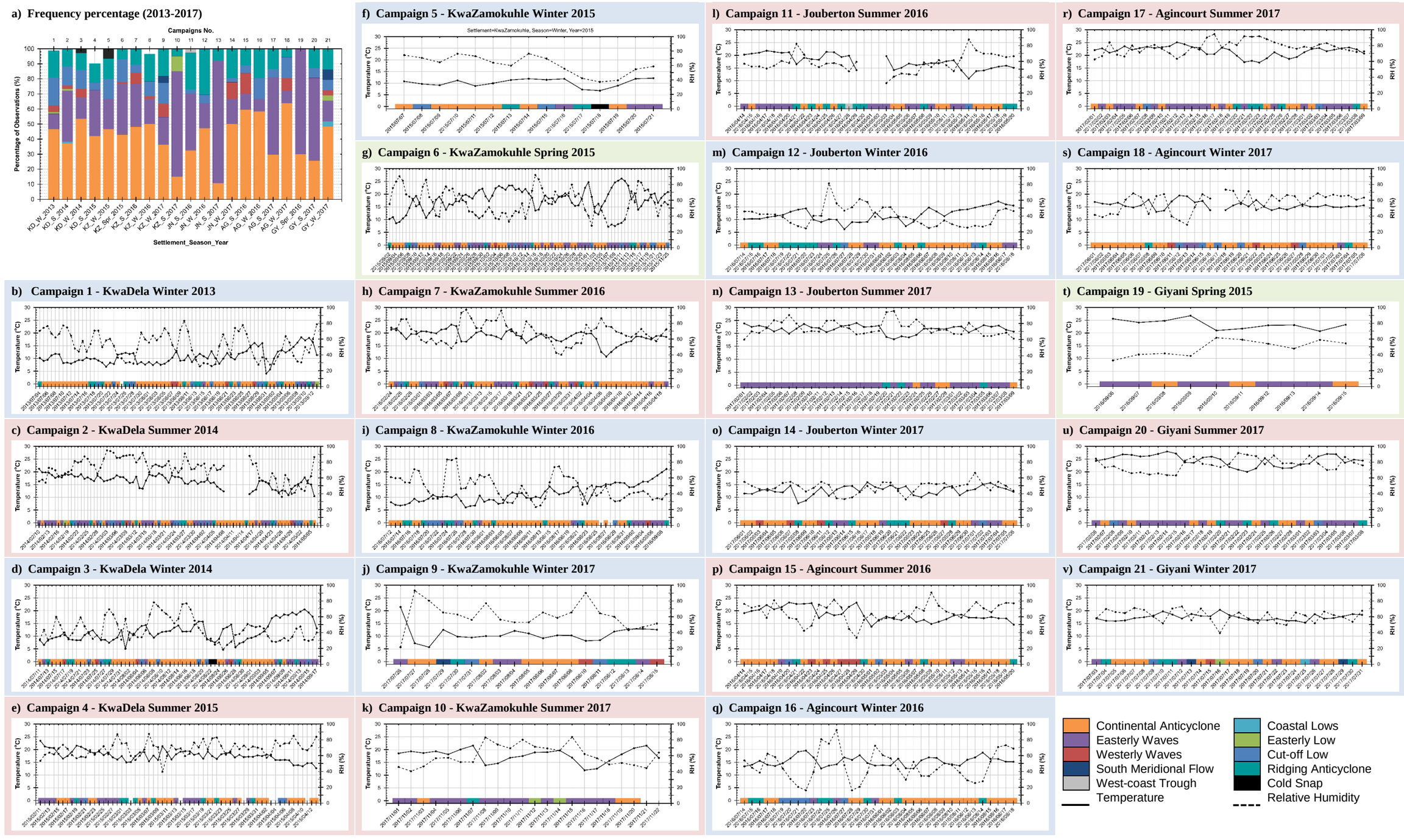


Figure 5.2 a) The frequency of occurrence (%) for synoptic circulation conditions observed during the sampling campaign conducted between 2013 and 2017. Time series for daily averaged temperature in °C (y-left) and percentage relative humidity (y-right) compared to the daily synoptic circulation conditions observed in b-e) KwaDela, f-k) KwaZamokuhle, l-o) Jouberton, p-s) Agincourt, and t-v) Giyani.

Anticyclonic synoptic circulation dominated (~70%) over the Agincourt region during 2016 *(Figure 5.2.a)*, whereas easterly flows were more prevalent during 2017 over both Agincourt and Giyani (51.35 % and 54.84%, respectively). In 2016, the aforementioned (anticyclones) existed for shorter periods (about a day) up to an extended period of seven (7) days, from 2016/05/14 to 2016/05/20. These conditions intermittently interrupted by westerly waves lasting up to three (3) days. In 2017, the easterly waves persisted for a number of consecutive days, the longest period being six (6) days in both Agincourt and Giyani, from 2017/01/11 to 2017/02/16. These conditions were broken up by the intrusion of anticyclonic conditions and less frequently by cut-off lows.

5.1.1.2.3. Winter

Similar to the summer, there were a total of three (3) winter campaigns performed in the Lowveld region. Yet again this included two (2) campaigns in Agincourt and a single campaign in Giyani (Campaign no. 16, 18 and 21 – *see Table 2.2*). The sampling was conducted between the months of June and August. The campaigns were also similar in length to those conducted during summer.

All three (3) sampling periods, namely Agincourt 2016 *(Figure 5.2.q)* and 2017 *(Figure 5.2.s)*, as well as Giyani 2017 *(Figure 5.2.v)* were dominated by prevailing anticyclonic synoptic circulation conditions (similar to winter periods over the Highveld region) occurring more than sixty per cent of the time *(Figure 5.2.a)*. In most incidences, the conditions kept on for a period of one (1) to four (4) days. However, the longest continuous period was eighteen (18) days, from 2016/08/04 to 2016/08/18, over Agincourt. A cut-off low existed over Agincourt for approximately four (4) days, from 2016/07/19 to 2016/07/22. This was the longest continuous occurrence of westerly disturbance throughout the study period.

The prevalence and duration of the individual synoptic circulation systems would have impacted on the concentration of air pollutants being recirculated over the specific regions in which the settlement are located. Typically, stable conditions are not conducive to the dispersion of air pollutants. This is important as the ambient concentrations impact the level of pollution found within the indoor environment.

5.1.2. Local wind fields

Local winds influence the dispersion and transportation of pollutants that are emitted at or close to the surface. The variability in the wind speeds recorded during each of the twenty-one (21) sampling campaigns, conducted between 2013 and 2017, are presented in *Figure 5.3*.

The settlements situated in the Highveld region, namely KwaDela, KwaZamokuhle, and Jouberton experienced median (±SD) summer wind speeds of 2.8 (±1.3), 2.1 (±1.7), and 1.8 (±1.9) $m.s^{-1}$, respectively. The average maximum winds speeds ranged between 6.0 and 9.2 $m.s^{-1}$, with Jouberton having lower maximum wind speeds than KwaDela and KwaZamokuhle. The winter median for KwaDela and Jouberton

were higher at 3.4 (±1.7) and 2.0 (±1.4) m.s^{-1}, while KwaZamokuhle had a slightly lower median of 1.7 (±1.7) m.s^{-1}. The average maximum wind speeds were higher during the winter compared to the summer, ranging between 6.5 and 12.3 m.s^{-1}. The spring transition period, in KwaZamokuhle, showed a median wind speed of 2.9 (±1.9) m.s^{-1} with an average maximum of 9.7 m.s^{-1}.

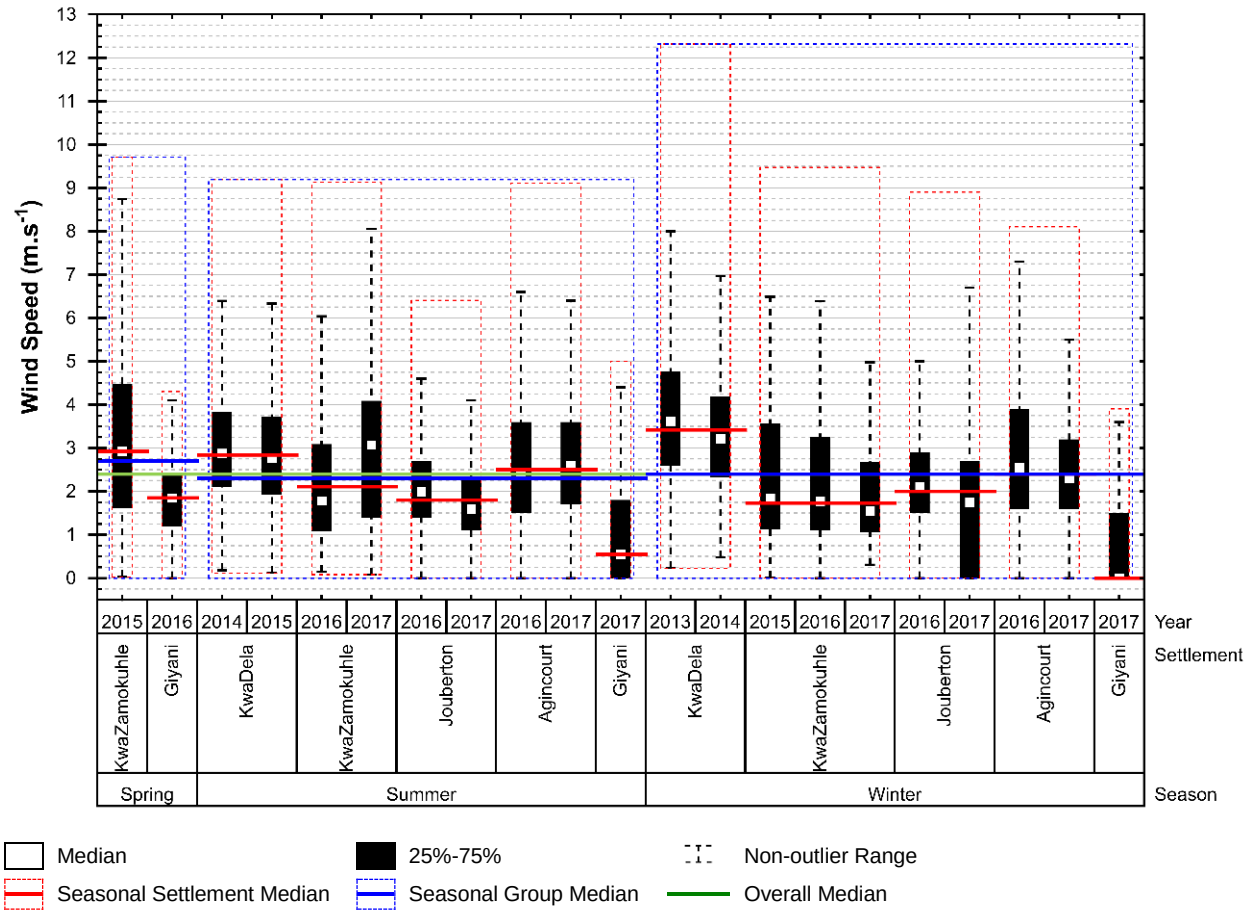


Figure 5.3 Box-plot showing the variability of hourly averaged wind speed (m.s^{-1}), for each sampling campaign, categorised by season, settlement, and year.

Settlement in the Lowveld regions, namely Agincourt and Giyani, had median summer wind speeds of 2.5 (±1.5) and 0.6 (±1.1) m.s^{-1}. The average maximum winds speeds were 9.1 and 5.0 m.s^{-1}, respectively. The winter medians were higher in Agincourt (3.5 (±1.4) m.s^{-1}), but lower in Giyani (0.1 (±1.0) m.s^{-1}). However, the average maximum wind speeds were lower than that of the summer for both settlements, being 8.1 and 3.9 m.s^{-1}, respectively. The spring period in Giyani had the highest median wind speed of 1.9 (±1.7) m.s^{-1} compared to the summer and winter campaigns conducted in this settlement.

Table 5.1 provides the comprehensive descriptive statistics related to the wind speeds, however, this is not sufficient to describe the flow. Wind roses are used to further describe the character of the surface flow.

Table 5.1 Descriptive statistics of the ambient wind speed ($m.s^{-1}$) for each sampling campaign, categorised by season, settlement, and year. (*Note:* includes the season averages for each settlement and region).

Season	Settlement	Year	Mean	SD	Min	1st	25th	Median	75th	99th	Max	% Valid N
Spring	KwaZamokuhle	2015	3.2	1.9	0.0	0.3	1.6	2.9	4.5	8.1	9.7	98.9
	Giyani	2016	1.7	1.1	0.0	0.0	1.2	1.9	2.4	4.1	4.3	100.0
	Average		3.1	1.9	0.0	0.0	1.5	2.7	4.3	8.0	9.7	99.5
Summer	KwaDela	2014	3.1	1.4	0.2	0.7	2.1	2.9	3.8	7.0	9.2	89.8
		2015	2.9	1.3	0.1	0.7	1.9	2.8	3.7	6.7	8.2	98.1
			3.0	1.3	0.1	0.7	2.0	2.8	3.8	6.8	9.2	93.3
	KwaZamokuhle	2016	2.2	1.5	0.1	0.3	1.1	1.8	3.1	7.1	8.6	100.0
		2017	2.9	1.9	0.1	0.1	1.4	3.1	4.1	7.9	9.1	95.3
			2.5	1.7	0.1	0.1	1.1	2.1	3.6	7.5	9.1	98.3
	Jouberton	2016	2.1	1.2	0.0	0.0	1.4	2.0	2.7	5.8	6.4	87.3
		2017	1.6	1.2	0.0	0.0	1.1	1.6	2.3	4.7	6.0	99.4
			1.9	1.2	0.0	0.0	1.3	1.8	2.5	5.2	6.4	79.7
	Highveld		2.5	1.4	0.1	0.3	1.5	2.4	3.3	6.5	7.9	95.0
	Agincourt	2016	2.6	1.5	0.0	0.0	1.5	2.4	3.6	6.2	7.8	99.9
		2017	2.7	1.5	0.0	0.0	1.7	2.6	3.6	6.9	9.1	100.0
			2.6	1.5	0.0	0.0	1.6	2.5	3.6	6.5	9.1	99.8
	Giyani	2017	1.0	1.1	0.0	0.0	0.0	0.6	1.8	4.3	5.0	100.0
	Lowveld		2.1	1.4	0.0	0.0	1.1	1.9	3.0	5.8	7.3	100.0
	Average		2.5	1.5	0.0	0.0	1.4	2.3	3.4	6.7	9.2	96.7
Winter	KwaDela	2013	3.9	1.8	0.2	0.7	2.6	3.6	4.8	8.9	11.5	80.5
		2014	3.4	1.6	0.5	0.8	2.3	3.2	4.2	9.3	12.3	95.8
			3.6	1.7	0.2	0.8	2.5	3.4	4.5	9.1	12.3	87.4
	KwaZamokuhle	2015	2.4	1.6	0.0	0.2	1.1	1.8	3.6	5.8	6.5	100.0
		2016	2.3	1.8	0.0	0.2	1.1	1.8	3.3	8.7	9.5	100.0
		2017	2.0	1.3	0.3	0.5	1.1	1.6	2.7	5.4	6.2	100.0
			2.3	1.7	0.0	0.2	1.1	1.7	3.2	8.0	9.5	98.9
	Jouberton	2016	2.3	1.3	0.0	0.0	1.5	2.1	2.9	7.3	8.9	100.0
		2017	1.8	1.5	0.0	0.0	0.0	1.8	2.7	6.7	8.9	100.0
			2.1	1.4	0.0	0.0	1.3	2.0	2.8	7.2	8.9	100.0
	Highveld		2.6	1.6	0.1	0.3	1.4	2.3	3.5	7.4	9.1	96.6
	Agincourt	2016	2.8	1.6	0.0	0.0	1.6	2.6	3.9	6.6	8.1	100.0
		2017	2.4	1.2	0.0	0.0	1.6	2.3	3.2	5.2	5.8	95.3
			2.6	1.4	0.0	0.0	1.6	2.4	3.5	6.1	8.1	97.6
	Giyani	2017	0.7	1.0	0.0	0.0	0.0	0.0	1.5	3.4	3.9	100.0
	Lowveld		2.0	1.3	0.0	0.0	1.1	1.6	2.9	5.1	5.9	98.4
	Average		2.7	1.8	0.0	0.0	1.4	2.4	3.7	8.0	12.3	97.2

5.1.2.1. Local wind fields in the Highveld region

5.1.2.1.1. KwaDela

The average winter *(Figure 5.4.a and g)* and summer *(Figure 5.4.d and j)* surface wind roses at KwaDela showed distinct flows from the north-west and east-north-east sectors.

In summer 2014 and 2015, during both the daytime *(Figure 5.4.e and k)* and night-time *(Figure 5.4.f and l)*, the surface flow was variable originating from both the easterly and westerly directions. Calm conditions prevailed for only a small frequency (range: 0.8% to 2.7%) of all summer observations. Wind flows ranging below 2.5 $m.s^{-1}$ occurred less frequently than those ranging above 2.5 $m.s^{-1}$.

The winter daytime surface flow for 2013 *(Figure 5.4.b)* and 2014 *(Figure 5.6.h)* were very similar as calm conditions were 0.8% and 1.2%, respectively. Flows originating from the western sectors had higher frequencies of strong (range: 3.5 to >5.0 $m.s^{-1}$) winds, while those from the east were equally strong but less common. Conditions were calm for 1.2 % and 1.5% of observations during the night-time, for both 2016 *(Figure 5.4.c)* and 2017 *(Figure 5.4.i)*. The winds originate mainly from the north-west at flows ranging between 1.0 and 5.0 $m.s^{-1}$.

5.1.2.1.2. KwaZamokuhle

The average spring *(Figure 5.5.d)*, summer *(Figure 5.5.g)* and winter *(Figure 5.5.a and j)* surface wind roses at KwaZamokuhle showed flows originating from various sectors with distinct differences between seasons.

In spring, between 06h00 and 18h00 *(Figure 5.5.e)*, the wind at KwaZamokuhle was variable with north-westerly and easterly winds occurring. Both the north-westerly and easterly winds were of high wind speeds (range: 3.5 to >5.0 $m.s^{-1}$), however, higher frequencies were observed from the western sector. During night-time *(Figure 5.5.f)*, there were calm conditions (<1.0 $m.s^{-1}$) for approximately fifteen (15) per cent of the observations with the remaining winds originating primarily from between a north-easterly and a south-south-easterly. Lower wind speeds (range: 1.0 to 3.5 $m.s^{-1}$) were observed more frequently at night, but still, there are stronger winds above 5.0 $m.s^{-1}$.

In summer, during both the daytime *(Figure 5.5.h)* and night-time *(Figure 5.5.i)*, the surface flow was variable originating from easterly, westerly, and southerly directions. Calm conditions prevailed for 9.5% and 27.1% of observations, respectively. The rest of the summer observations were similar to that of spring.

The winter daytime surface flow for 2015 *(Figure 5.5.b)* and 2016 *(Figure 5.5.k)* were very similar in nature with calm conditions occurring for 10.8% and 15.4% of the observations. The flows originated from the north-east, north-west, south-west and south-easterly directions. Flows from the south-east are weaker

(range: 1.0 to 2.5 m.s^{-1}) and occur less frequently compared to the other sectors. The winds flowing from the other sectors range from 2.5 to more than 5.0 m.s^{-1}. Conditions were calm for 30.7% and 19.5% of observations during the night-time, for 2015 *(Figure 5.5.c)* and 2016 *(Figure 5.5.l)*. Flows dominated from the south-easterly sectors with wind speeds below 4.0 m.s^{-1}.

5.1.2.1.3. Jouberton

The average surface wind roses at Jouberton showed distinct flows from the north-westerly sector during summer 2016 *(Figure 5.6.a)* and from both the north-west and the east-north-east during 2017 *(Figure 5.6.g)*. The winter 2016 *(Figure 5.6.d)* and 2017 *(Figure 5.6.j)* campaigns showed variable flow from the north-west and to a lesser degree from a southerly direction.

In summer 2016 and 2017, between 06h00 and 18h00 *(Figure 5.6.b and h)*, conditions were calm for 5.6% and 9.6% of observations, while during the night *(Figure 5.6.c and i)* these increased to 15.4% and 25.0% respectively. Wind flows ranging between 1.0 and 3.5 m.s^{-1} occur more often in the north-westerly sector. Flows above 3.5 m.s^{-1} are less prevalent.

The winter daytime surface flow for 2016 *(Figure 5.6.e)* and 2017*(Figure 5.6.k)* were very similar in nature. However, there is a significant difference in the frequency (4.7% and 23.7 %) of calms conditions observed during 2016 and 2017, respectively. Flows originating from the north-west have higher frequencies of weaker winds, while those from the west are much stronger (range: 2.5 to >5.0 m.s^{-1}) but occur less frequently. Conditions were calm for 12.4 % and 34.4% of observations during the night-time, for both 2016 *(Figure 5.6.f)* and 2017 *(Figure 5.6.l)*. The winds originate mainly from the north-west at flows ranging between 1.0 and 5.0 m.s^{-1}.

5.1.2.2. Local wind fields in the Lowveld region

5.1.2.2.1. Agincourt

The average surface wind roses at Agincourt showed distinct flows from the easterly sector during summer 2016 *(Figure 5.7.a)* and 2017 *(Figure 5.7.g)*. The winter 2016 *(Figure 5.7.d)* and 2017 *(Figure 5.7.j)* periods showed variable flow from the east-north-east and the west-south-west sectors.

In summer 2016 and 2017, between 06h00 and 18h00 *(Figure 5.7.b and h)*, conditions were calm for 8.5% and 4.9% of observations, while during the night *(Figure 5.7.c and i)* these increased to 14.6% and 13.7% respectively. Wind flows ranging between 1.0 and 2.5 m.s^{-1} occur less frequently than those ranging between 2.5 and 5.0 m.s^{-1} for all periods during summer. It is important to note that there are low frequencies of flows origination from the south and east sectors, however, this is almost negligible. Wind speeds exceed 5.0 m.s^{-1} on numerous occasions when originating from an easterly direction.

The winter daytime surface flow for 2016 *(Figure 5.7.e)* and 2017*(Figure 5.7.k)* were very similar in nature with calm conditions occurring for 3.0% and 3.9% of the observations. The flows originating from the east-north-east have higher frequencies of winds above 2.5 $m.s^{-1}$, while flows coming from the east tend to have higher occurrences of slower-moving winds (<2.5 $m.s^{-1}$).

Conditions were calm for about ten (10) per cent of observations during the night-time, for both 2016 *(Figure 5.7.f)* and 2017 *(Figure 5.7.l)*. During 2016 the flows dominated from both the north-easterly and south-westerly sectors with wind speeds above 5.0 $m.s^{-1}$. In 2017 flows coming from the east were less frequent but still strong, whereas winds from the west were never above 5.0 $m.s^{-1}$. Winds having speeds less than 2.5 $m.s^{-1}$ are more frequent from the west during both the 2016 and 2017 sampling periods.

5.1.2.2.2. Giyani

The spring *(Figure 5.8.a)*, summer *(Figure 5.8.d)*, and winter *(Figure 5.8.g)* surface wind roses at Giyani showed a distinct flow from the easterly sector during daytime and night-time.

In spring, between 06h00 and 18h00 *(Figure 5.8.b)*, the wind at Giyani was variable with north-easterly and east-south-easterly winds occurring. The north-easterly winds were of lower wind speeds (range: 1.0 to 2.5 $m.s^{-1}$) but higher frequency (~14%) of occurrence, whereas the east-south-easterly winds were less prevalent (<12%) with greater wind speeds (range: 1.0 to >5.0 $m.s^{-1}$). During night-time *(Figure 5.8.c)*, there were calm conditions (<1.0 $m.s^{-1}$) for approximately sixty-five (66) per cent of the observations with the remaining winds were originating primarily from the east-south-east at similar speeds as during the day-time, however at a higher frequency (~20%).

In summer, during both the daytime *(Figure 5.8.e)* and night-time *(Figure 5.8.f)*, the surface flow was variable originating between the east-north-easterly and east-south-easterly directions. Calm conditions prevailed for 39.5% and 63.0% of observations, respectively. The wind flow mostly ranged between 1.0 and 3.5 $m.s^{-1}$, with only a small fraction of the flow reaching 5.0 $m.s^{-1}$. There were no winds above 5.0 $m.s^{-1}$ during this sampling period.

Winter daytime *(Figure 5.8.h)* and night-time *(Figure 5.8.i)* surface winds in Giyani originated from the same direction as the summer surface wind flow, however, during the day east-north-easterly flow was dominant while the east-south-easterly flow was more frequent during the night. Calm conditions were more prevalent during the winter, being 46.2% and 83.3%, respectively for day and night observations. The wind flow mostly ranged between 1.0 and 3.5 $m.s^{-1}$, with only a small fraction of the flow reaching 4.0 $m.s^{-1}$.

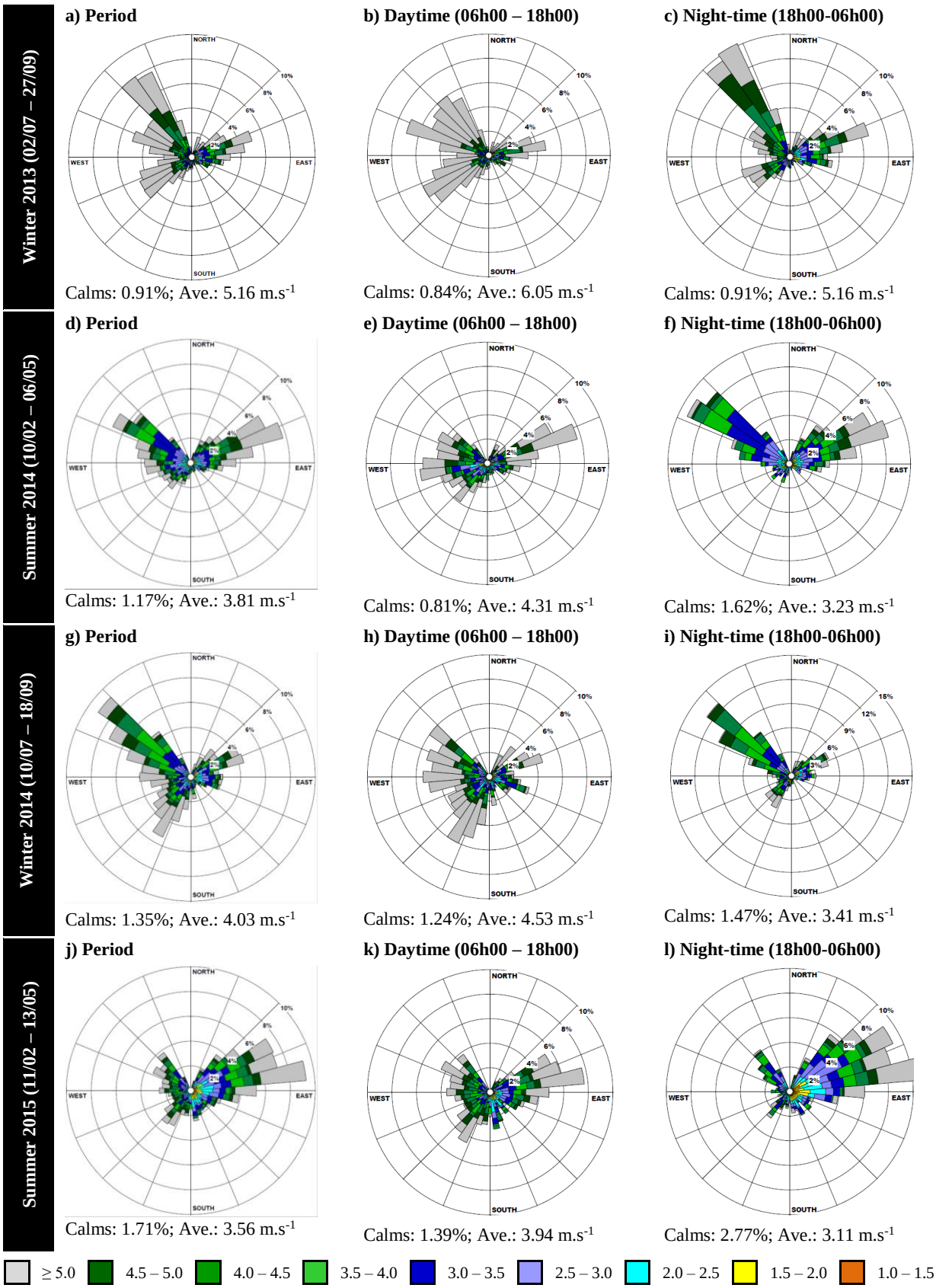


Figure 5.4. Wind roses depicting the hourly averaged wind speed and wind direction for the sampling period, day-time (06:00-18:00), and night-time (18:00-06:00) in KwaDela during winter 2013 (a-c); summer 2014 (d-f); winter 2014 (g-i); summer 2015 (j-l).

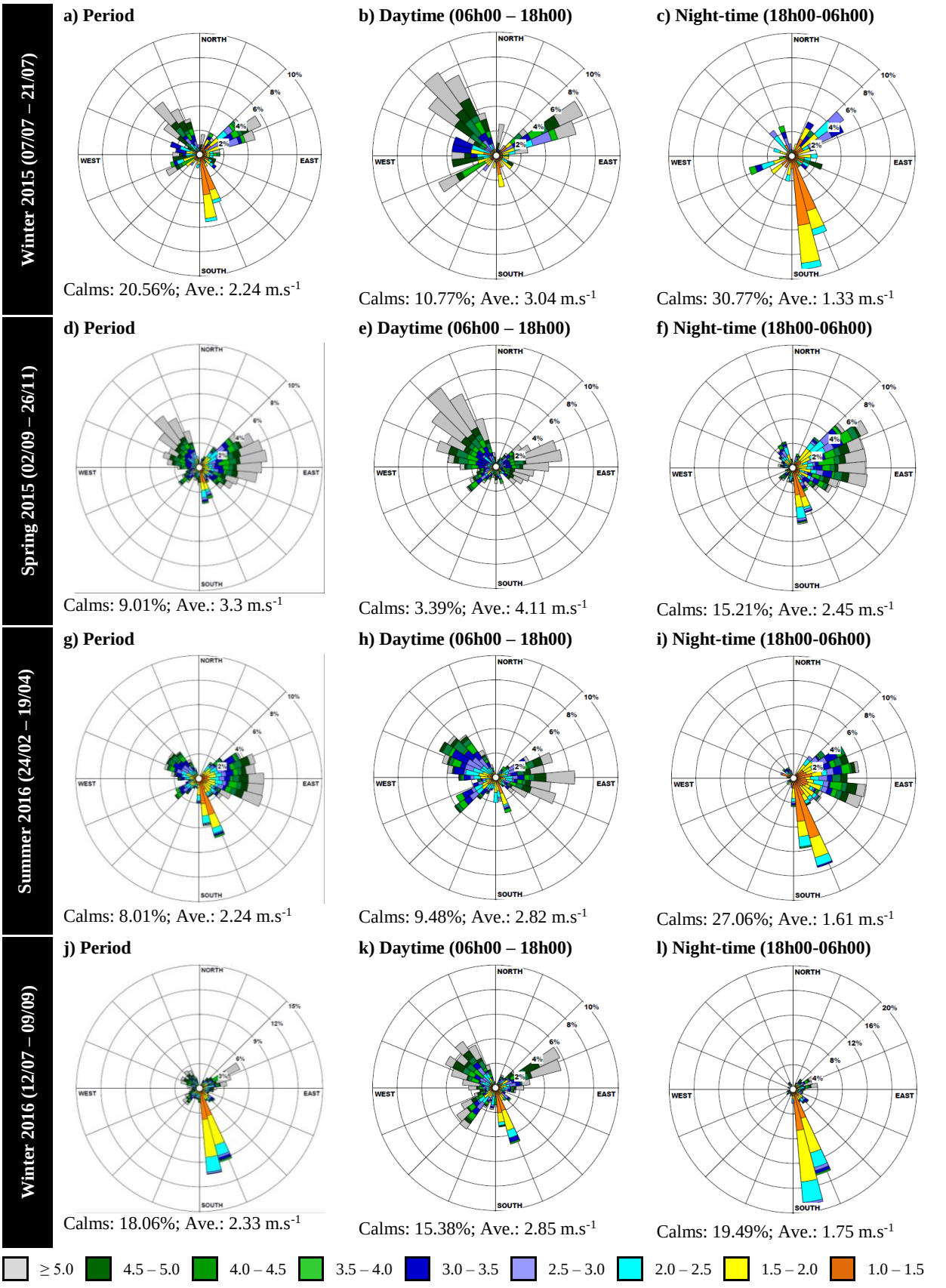


Figure 5.5. Wind roses depicting the hourly averaged wind speed and wind direction for the sampling period, day-time (06:00-18:00), and night-time (18:00-06:00) in KwaZamokuhle during winter 2015 (a-c); spring 2015 (d-f); summer 2016 (g-i); winter 2016 (j-l).

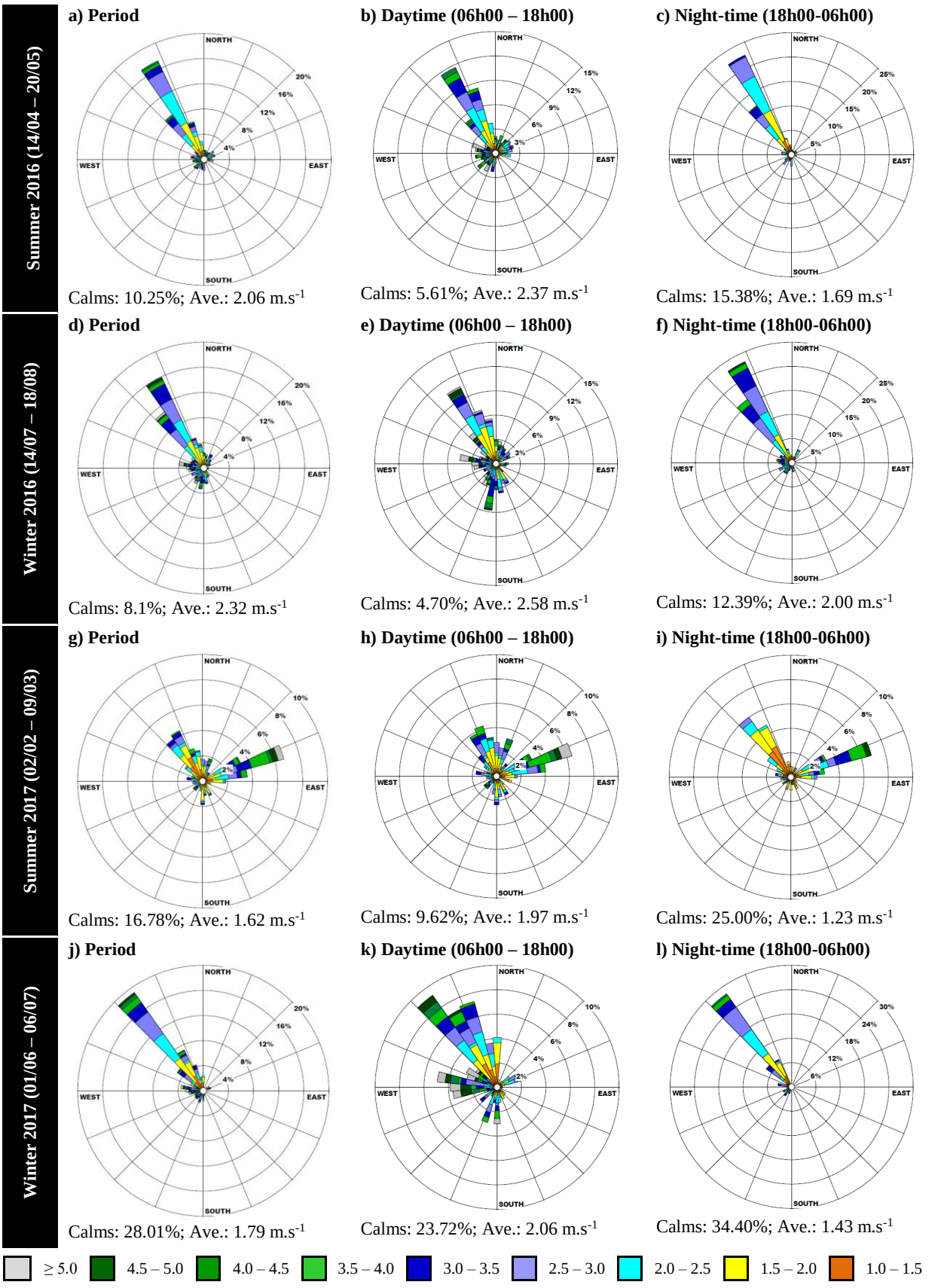


Figure 5.6. Wind roses depicting the hourly averaged wind speed and wind direction for the sampling period, day-time (06:00-18:00), and night-time (18:00-06:00) in Jouberton during summer 2016 (a-c); winter 2016 (d-f); summer 2017 (g-i); winter 2017 (j-l).

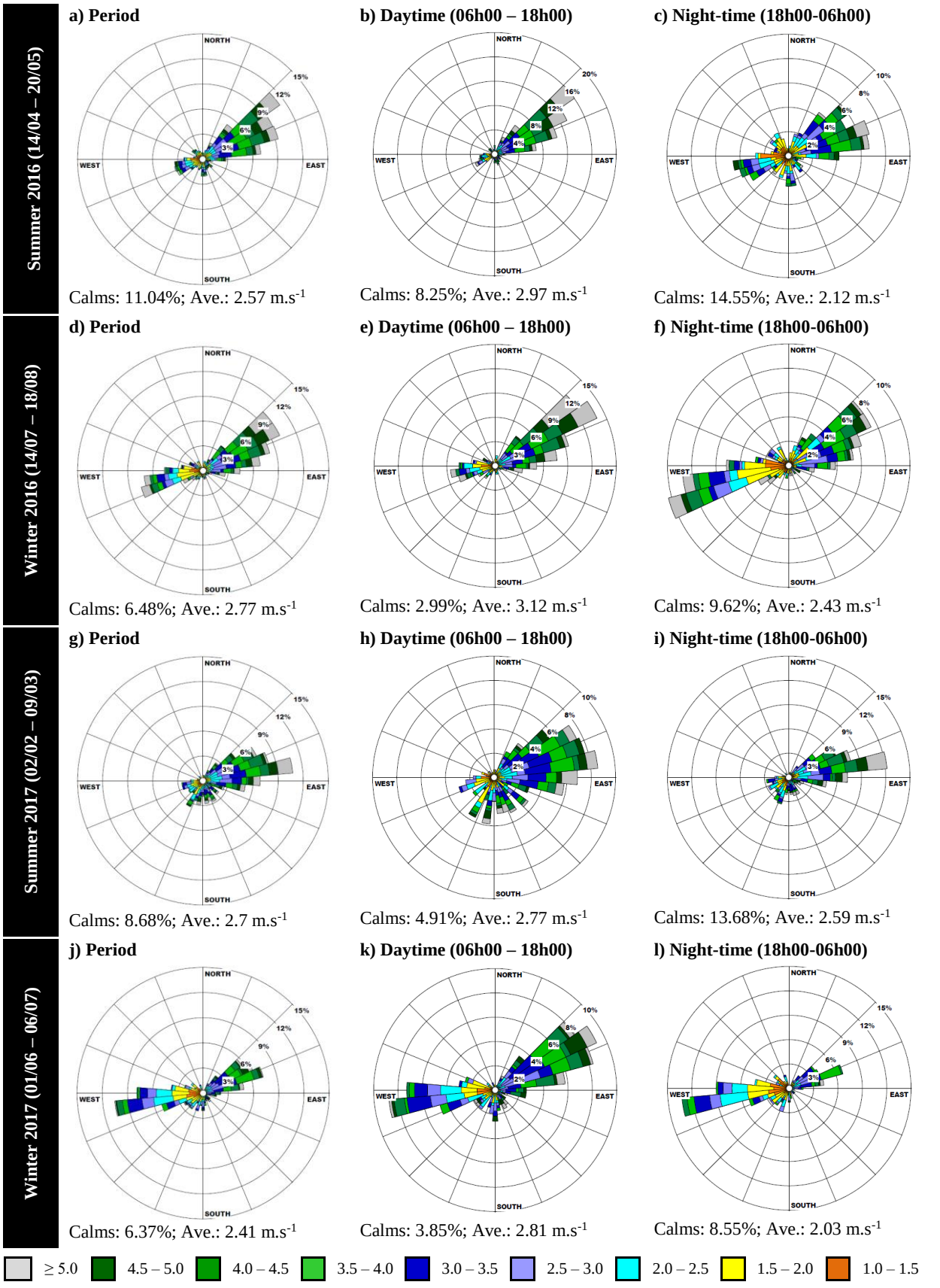


Figure 5.7. Wind roses depicting the hourly averaged wind speed and wind direction for the sampling period, day-time (06:00-18:00), and night-time (18:00-06:00) in Agincourt during summer 2016 (a-c); winter 2016 (d-f); summer 2017 (g-i); winter 2017 (j-l).

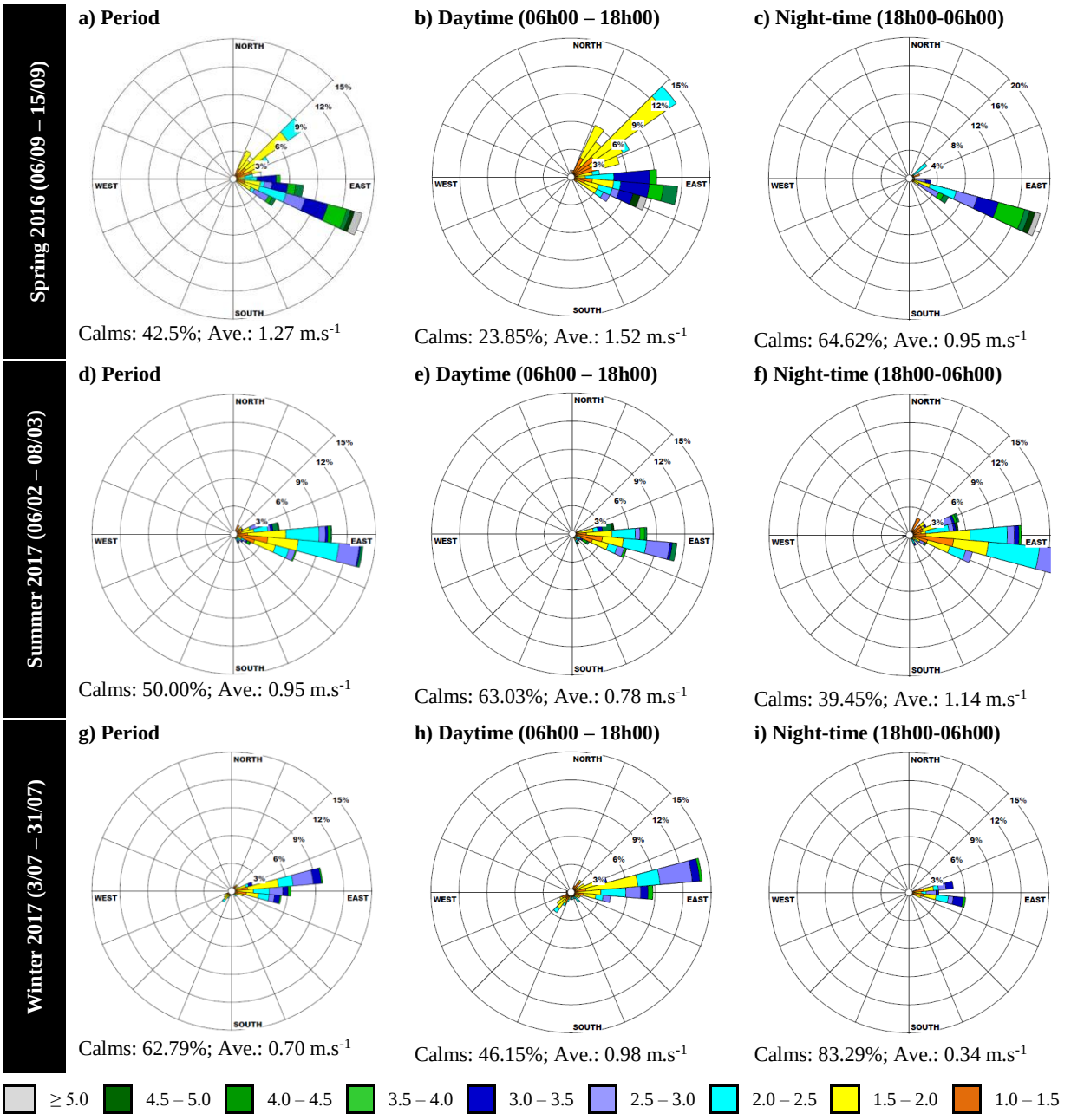


Figure 5.8. Wind roses depicting the hourly averaged wind speed and wind direction for the sampling period, day-time (06:00-18:00), and night-time (18:00-06:00) in Giyani during spring 2016 (a-c); summer 2017 (d-f); and winter 2017 (g-i).

5.1.3. Temperature and relative humidity

Temperature and relative humidity play a role in the behaviour of air pollution (described previously), however, it also has a significant impact on the behaviours of people. This includes, for instance, their residential combustion activities and the manner (frequency and duration) in which they might ventilate their homes. It is thus important to have a good understanding of these variables and how it varies during the study period. The daily march, diurnal patterns and seasonal variations are explored and compared to the climatic data *(discussed previously in Section 2.2)*.

The time series presenting the daily march of the hourly averaged temperature and relative humidity, for each individual sampling campaign, was previously graphed in conjunction with the synoptic conditions in *Figure 5.2 b* to *v*. The time series indicated continual changes in mean temperatures and relative humidity across each day sampled during the study. It is expected that this daily variability will impact particulate pollution concentrations.

The average diurnal pattern for temperature and relative humidity in each settlement, categorised by the season, revealed the expected diurnal patterns for both temperature and relative humidity. The highest median temperatures usually occur between 10h00 and 14h00 and the lowest median between 04h00 and 07h00. The relative humidity pattern is inverse to that of temperature, thus the highest medians occur between 04h00 and 07h00, while the lowest medians between 10h00 and 18h00. This is true across all seasons regardless of where the settlement is located, however, the actual levels observed are impacted by geographic location.

The variability in the hourly averaged temperature (°C) and relative humidity (%) recorded during each of the twenty-one (21) sampling campaigns, conducted between 2013 and 2017, are presented in *Figure.5.9 a* and *b,* respectively. The descriptive statistics are also given in *Table 5.2* and *Table 5.3*, respectively.

The overall seasonal median temperatures (across all settlements and campaigns) for spring, summer and winter were 18.4 (±7.1), 18.8 (±5.4), and 12.5 (±6.9), respectively. While the median relative humidity across the season were 60.0 (±24.0), 68.8 (±20.6), and 49.9 (±25.7), respectively. These observations are explained in further detail for each of the twenty-one (21) sampling campaigns conducted during this study.

5.1.3.1. Temperature and relative humidity in the Highveld region

5.1.3.1.1. Spring

The spring sampling, conducted in KwaZamokuhle, indicated median (±SD) temperature and relative humidity of 17.2 (±7.0) °C and 58.4 (±27.7) %. The average maximums were 34.5 °C and 100%, with the average minimums as 1.9 °C and 5.6 %, respectively.

5.1.3.1.2. Summer

The six (6) summer campaigns conducted in the Highveld, had median (±SD) temperature and relative humidity of 17.6 (±5.3) °C and 70.3 (±22.5) %. The average maximums were 30.9°C and 98.2%, with the average minimums as 5.9°C and 14.2 %, respectively. KwaDela experienced the lowest mean temperatures, followed by KwaZamokuhle and Jouberton. The average maximum temperatures for all campaigns during the summer ranged between 29 and 30°C. The average minimums for KwaDela and KwaZamokuhle ranged

between 1.7 and 7.0°C, however, Jouberton showed higher variability ranging between 4.8 and 15.0°C from 2016 to 2017.

5.1.3.1.3. Winter

The seven (7) winter campaigns conducted in the Highveld, had median (±SD) temperature and relative humidity of 10. (±7.0) °C and 48.6 (±25.5) %. The average maximums were 27.7 °C and 97.7%, with the average minimums as -3.5 °C and 7.2 %, respectively. All three (3) settlements had similar averaged mean temperatures, ranging between 10.2 and 12.7°C. KwaDela and KwaZamokuhle had higher averaged maximums (above 30°C), compared to Jouberton. KwaZamokuhle was on average ~2 to 3°C colder than KwaDela and Jouberton (looking at the average minimums).

5.1.3.2. Temperature and relative humidity in the Lowveld region

5.1.3.2.1. Spring

The spring sampling, conducted in Giyani, indicated median (±SD) temperature and relative humidity of 25.0 (±5.0) °C and 65.0 (±20.3) %. The average maximums were 37.9 °C and 95.0%, with the average minimums as 17.3 °C and 22.0 %, respectively. These were significantly higher than the springtime measurements in KwaZamokuhle (Highveld).

5.1.3.2.2. Summer

The three (3) summer campaigns had median (±SD) temperature and relative humidity of 20.8 (±3.8) °C and 77.7 (±16.9) %. The average maximums were 32.4 °C and 98%, with the average minimums as 13.6 °C and 25.3 %, respectively. Giyani had a higher average maximum by ~2°C, compared to Agincourt. The minimum concentrations were higher than those experienced in the Highveld region.

5.1.3.2.3. Winter

The Lowveld winter campaigns had median (±SD) temperature and relative humidity of 15.5 (±4.8) °C and 54.7 (±21.9) %. The average maximums were 29.3 °C and 96.7%, with the average minimums as 4.0 °C and 10.3 %, respectively. Giyani had a higher average maximum by ~5°C, compared to Agincourt. Minimum temperatures were higher by ~7.0°C, compared to the Highveld.

These observations made in the Highveld and Lowveld regions during in spring, summer, and winter are consistent with long term (1981-2010) climatic record for the Bethal *(Figure 2.6)*, Klerksdorp *(Figure 2.10)*, Phalaborwa *(Figure 2.14)* and Thohoyandou *(Figure 2.12)* motoring stations *(see Section 2.2.2)*.

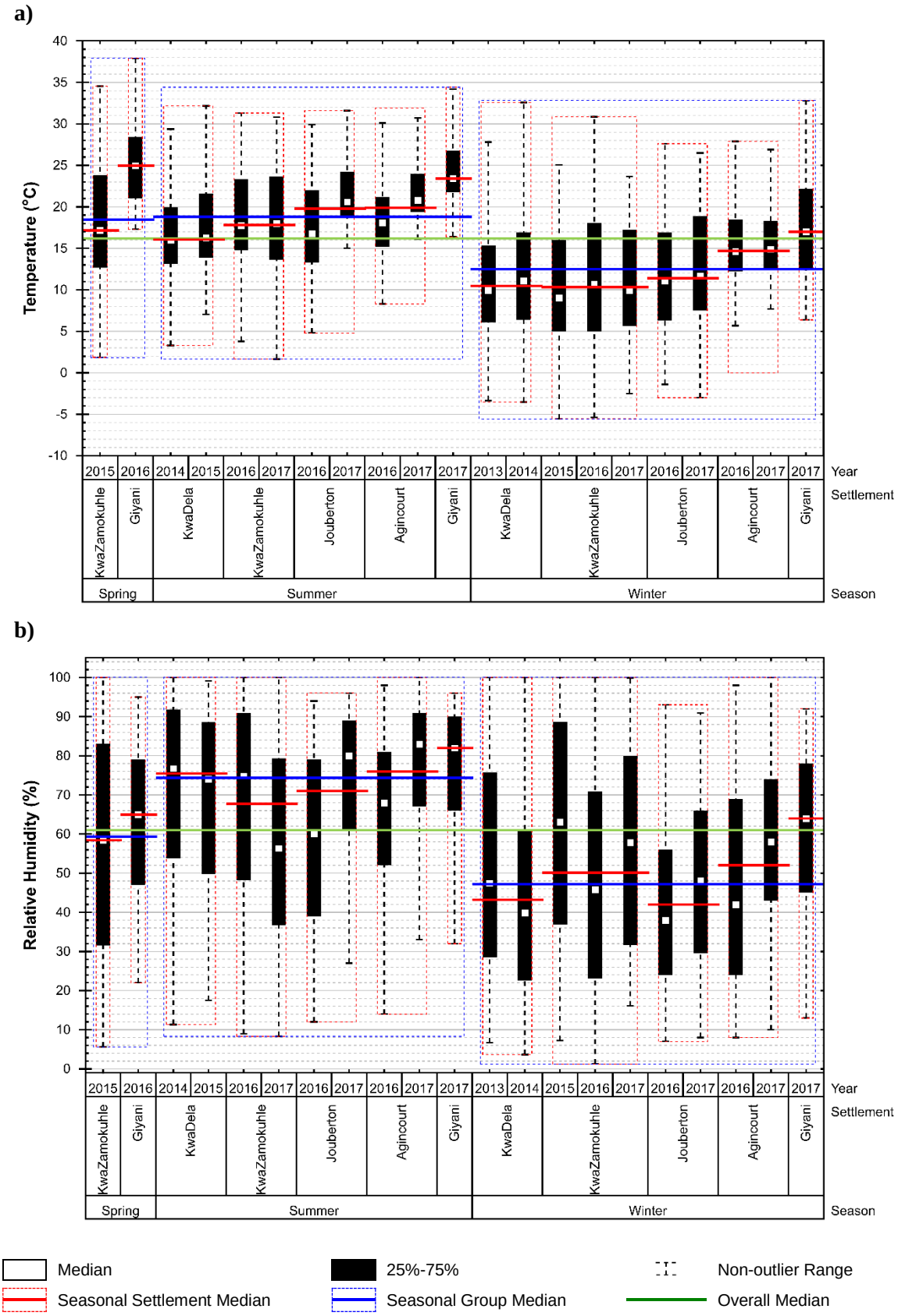


Figure.5.9 Box-plot showing the variability of hourly averaged temperature (°C) and relative humidity (%), for each sampling campaign, categorised by season, settlement, and year.

Table 5.2 Descriptive statistics of the ambient temperature (°C) for each sampling campaign, categorised by season, settlement, and year. (Note: includes the season averages for each settlement and region).

Season	Settlement	Year	Mean	SD	Min	1st	25th	Median	75th	99th	Max	% Valid N
Spring	KwaZamokuhle	2015	18.2	7.0	1.9	5.1	12.7	17.2	23.8	32.6	34.5	98.9
	Giyani	2016	25.3	5.0	17.3	17.4	21.0	25.0	28.5	37.4	37.9	100.0
	Average		**18.9**	**7.1**	**1.9**	**5.4**	**13.2**	**18.4**	**24.7**	**33.7**	**37.9**	**99.0**
Summer	KwaDela	2014	16.4	4.8	3.3	5.8	13.2	16.0	19.9	27.3	29.4	89.8
		2015	17.7	5.0	7.0	9.0	13.9	16.3	21.6	29.6	32.2	98.1
			17.0	*4.9*	*3.3*	*7.0*	*13.6*	*16.0*	*20.5*	*28.1*	*32.2*	*93.3*
	KwaZamokuhle	2016	18.6	5.8	3.8	6.5	14.8	17.7	23.4	29.8	31.3	100.0
		2017	18.4	6.4	1.7	5.9	13.6	18.0	23.7	29.9	30.8	95.3
			18.5	*6.0*	*1.7*	*6.1*	*14.4*	*17.8*	*23.5*	*29.8*	*31.3*	*98.3*
	Jouberton	2016	17.6	5.7	4.8	7.1	13.3	16.8	22.0	29.4	29.9	87.3
		2017	21.7	3.8	15.0	15.8	18.8	20.6	24.2	30.3	31.6	99.4
			19.8	*5.2*	*4.8*	*7.9*	*16.5*	*19.8*	*23.3*	*29.8*	*31.6*	*93.4*
	Highveld		18.4	5.3	5.9	8.4	14.6	17.6	22.5	29.4	30.9	95.0
	Agincourt	2016	18.5	4.2	8.3	11.2	15.2	18.1	21.2	29.7	31.9	99.9
		2017	21.6	3.3	16.1	16.3	19.4	20.8	24.0	29.6	31.0	100.0
			20.0	*4.1*	*8.3*	*11.7*	*17.1*	*19.9*	*22.3*	*29.6*	*31.9*	*99.9*
	Giyani	2017	24.5	3.8	16.4	18.2	21.8	23.4	26.8	33.5	34.4	100.0
	Lowveld		21.5	3.8	13.6	15.2	18.8	20.8	24.0	30.9	32.4	100.0
	Average		**19.0**	**5.4**	**1.7**	**7.3**	**15.0**	**18.8**	**22.8**	**30.7**	**34.4**	**96.0**
Winter	KwaDela	2013	10.8	6.1	-3.4	-1.0	6.1	10.0	15.4	25.3	27.8	80.5
		2014	11.9	7.1	-3.5	-1.0	6.4	11.1	17.0	28.9	32.6	95.8
			11.3	*6.6*	*-3.5*	*-1.0*	*6.2*	*10.5*	*16.2*	*27.8*	*32.6*	*87.4*
	KwaZamokuhle	2015	10.2	7.1	-5.5	-4.2	5.0	9.0	16.0	24.0	25.1	100.0
		2016	11.5	8.3	-5.4	-3.4	5.0	10.7	18.1	28.5	30.9	100.0
		2017	11.0	6.7	-2.5	-1.1	5.6	9.9	17.3	23.3	23.7	100.0
			11.2	*7.9*	*-5.5*	*-3.2*	*5.2*	*10.3*	*17.5*	*28.1*	*30.9*	*98.9*
	Jouberton	2016	11.9	6.8	-1.4	-0.1	6.3	11.1	17.0	25.8	27.6	100.0
		2017	12.7	6.7	-3.0	-0.3	7.5	11.7	18.9	24.9	26.5	100.0
			12.3	*6.8*	*-3.0*	*-0.1*	*7.1*	*11.4*	*17.9*	*25.2*	*27.6*	*100.0*
	Highveld		11.4	7.0	-3.5	-1.6	6.0	10.5	17.1	25.8	27.7	96.6
	Agincourt	2016	15.3	4.4	5.7	7.5	12.2	14.6	18.5	26.4	27.9	100.0
		2017	15.7	4.1	0.0	9.0	12.5	14.9	18.3	25.8	27.1	95.3
			15.5	*4.2*	*0.0*	*7.8*	*12.4*	*14.7*	*18.4*	*26.2*	*27.9*	*97.6*
	Giyani	2017	17.4	5.8	6.4	7.4	12.6	17.0	22.2	30.3	32.8	100.0
	Lowveld		16.1	4.8	4.0	8.0	12.4	15.5	19.7	27.5	29.3	98.4
	Average		**12.6**	16.1	4.8	4.0	8.0	12.4	15.5	19.7	27.5	29.3

Table 5.3 Descriptive statistics of the ambient relative humidity (%) for each sampling campaign, categorised by season, settlement, and year. (*Note:* includes the season averages for each settlement and region).

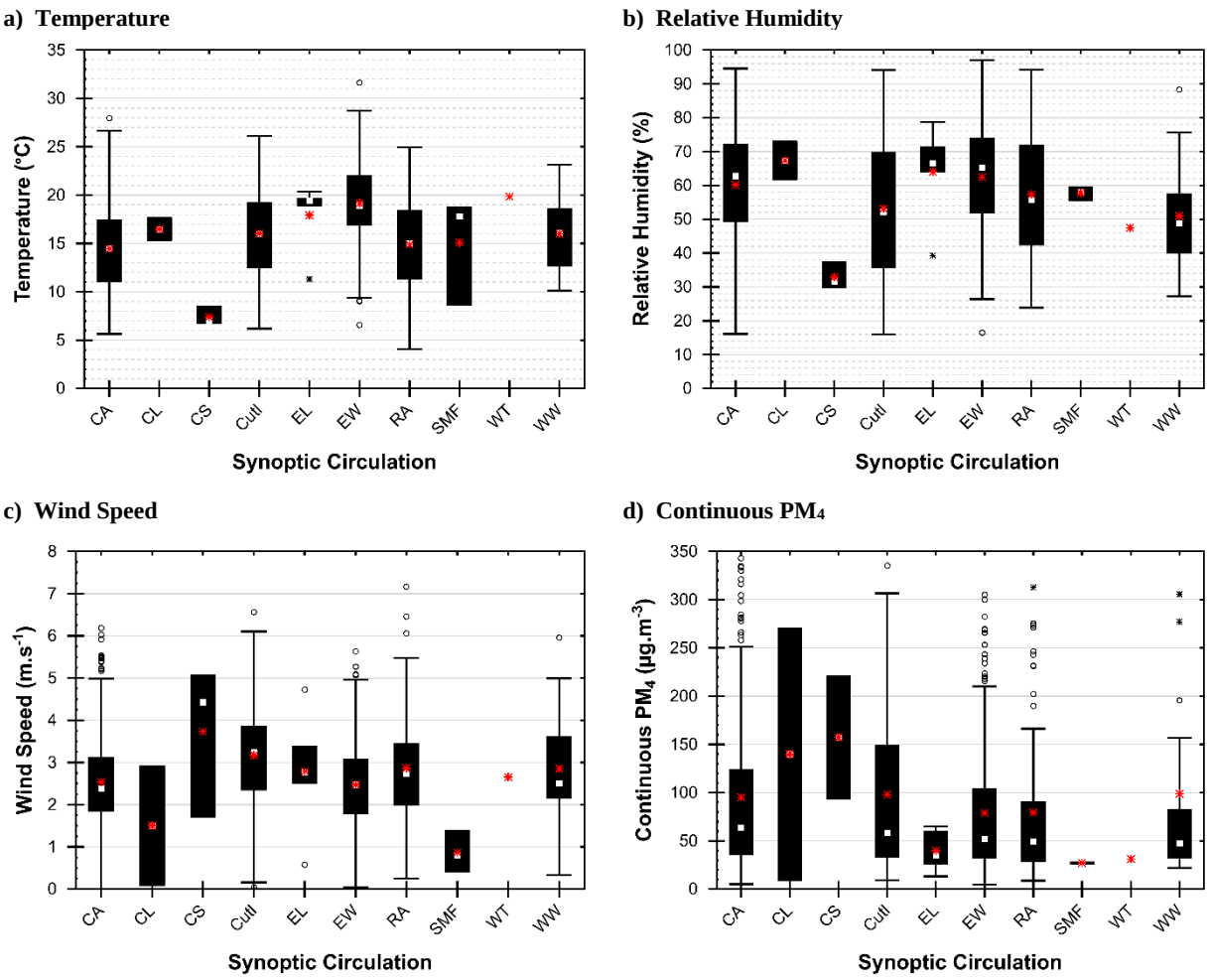
Season	Settlement	Year	Mean	SD	Min	1st	25th	Median	75th	99th	Max	% Valid N
Spring	KwaZamokuhle	2015	56.8	27.7	5.6	10.3	31.6	58.4	83.1	99.6	100.0	98.9
	Giyani	2016	63.1	20.3	22.0	23.0	47.0	65.0	79.0	94.0	95.0	100.0
	Average		60.0	24.0	13.8	16.7	39.3	61.7	81.1	96.8	97.5	99.5
Summer	KwaDela	2014	71.2	23.5	11.3	16.9	53.8	76.7	91.8	99.9	100.0	89.8
		2015	68.8	22.1	17.5	21.4	49.7	74.0	88.6	98.5	99.1	98.1
			70.1	22.9	11.3	19.1	51.5	75.5	90.1	99.7	100.0	93.3
	KwaZamokuhle	2016	68.6	24.9	8.9	15.7	48.2	74.8	90.9	100.0	100.0	100.0
		2017	57.2	25.1	8.3	10.6	36.7	56.3	79.3	99.5	100.0	95.3
			64.5	25.6	8.3	13.3	41.3	67.7	89.0	100.0	100.0	98.3
	Jouberton	2016	58.3	22.0	12.0	17.0	39.0	60.0	79.0	93.0	94.0	87.3
		2017	74.2	17.2	27.0	35.0	61.0	80.0	89.0	96.0	96.0	99.4
			66.7	21.2	12.0	18.0	50.0	71.0	85.0	96.0	96.0	93.4
	Highveld		66.4	22.5	14.2	19.4	48.1	70.3	86.4	97.8	98.2	95.0
	Agincourt	2016	65.9	18.5	14.0	21.0	52.0	68.0	81.0	97.0	98.0	99.9
		2017	78.2	16.2	30.0	36.0	67.0	83.0	91.0	100.0	100.0	100.0
			72.1	18.4	14.0	26.0	59.0	76.0	88.0	100.0	100.0	99.9
	Giyani	2017	76.9	15.9	32.0	40.0	66.0	82.0	90.0	95.0	96.0	100.0
	Lowveld		73.7	16.9	25.3	32.3	61.7	77.7	87.3	97.3	98.0	100.0
	Average		68.8	20.6	17.9	23.7	52.6	72.8	86.7	97.7	98.1	96.6
Winter	KwaDela	2013	52.1	27.7	6.7	9.8	28.5	47.4	75.7	100.0	100.0	80.5
		2014	44.1	25.9	3.7	6.7	22.6	39.8	61.1	99.8	100.0	95.8
			48.2	27.1	3.7	7.7	25.5	43.2	68.4	100.0	100.0	87.4
	KwaZamokuhle	2015	61.1	28.3	7.3	8.4	36.9	63.0	88.7	100.0	100.0	100.0
		2016	47.8	28.1	1.3	5.0	23.1	45.8	70.8	99.7	100.0	100.0
		2017	57.8	26.4	16.1	16.9	31.7	57.9	80.0	99.4	99.9	100.0
			51.8	28.3	1.3	5.2	26.5	50.1	77.0	99.8	100.0	97.8
	Jouberton	2016	40.4	20.7	7.0	8.0	24.0	38.0	56.0	88.0	93.0	100.0
		2017	48.2	21.1	8.0	12.0	29.5	48.0	66.0	85.0	91.0	100.0
			44.3	21.3	7.0	9.0	27.0	42.0	61.0	87.0	93.0	100.0
	Highveld		50.2	25.5	7.2	9.5	28.0	48.6	71.2	96.0	97.7	96.6
	Agincourt	2016	46.9	25.4	8.0	10.0	24.0	42.0	69.0	97.0	98.0	100.0
		2017	57.4	20.1	10.0	14.0	43.0	58.0	74.0	93.0	100.0	95.3
			52.0	23.5	8.0	10.0	32.0	52.0	72.0	97.0	100.0	97.6
	Giyani	2017	61.0	20.1	13.0	17.0	45.0	64.0	78.0	91.0	92.0	100.0
	Lowveld		55.1	21.9	10.3	13.7	37.3	54.7	73.7	93.7	96.7	98.4
	Average		49.9	25.7	1.3	8.0	28.0	47.2	71.0	100.0	100.0	94.4

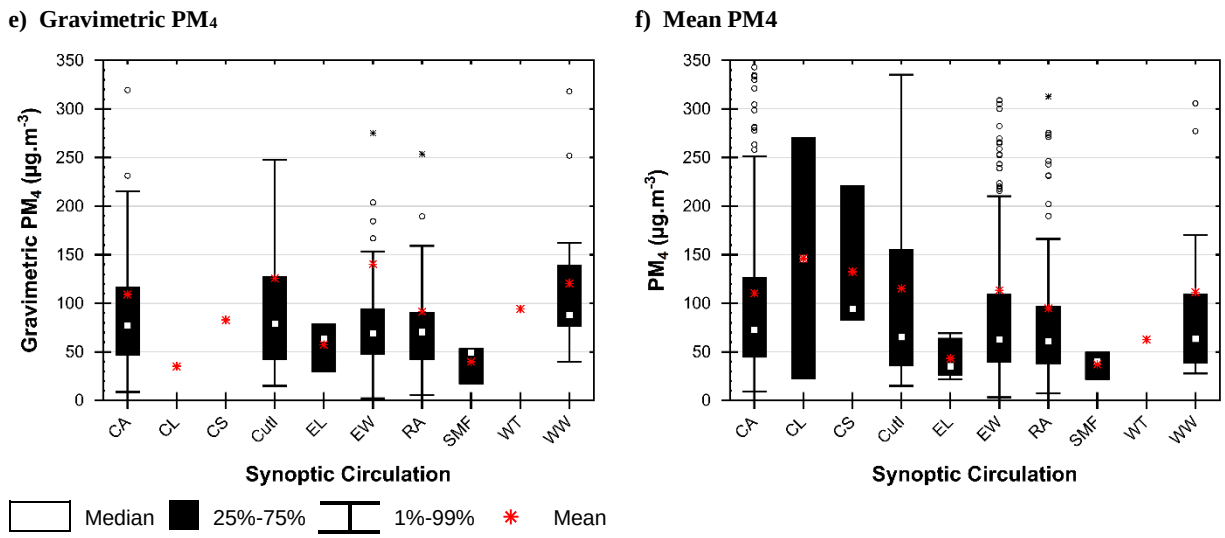
5.2. Local meteorology vs residential indoor PM_4 mass concentrations

Nine-hundred-and-twenty-seven (927) observational days were considered for this comparison, of which nine-hundred-and-nineteen (919) days had available regional synoptic circulation classifications.

The most prevalent synoptic circulation pattern *(see Section 5.1.1)* included the continental anticyclones followed by the easterly waves, ridging anticyclones, cut-off lows, and westerly waves. These synoptic circulation patterns will be investigated in further detail, thus excluding the coastal lows, easterly lows, southerly meridional flow, west-coast troughs, and cold snaps.

The local meteorological conditions and indoor PM_4 mass concentrations, categorised by the synoptic circulations, are summarised in *Figure.5.10*. These aspects are discussed in further detail based on the synoptic circulation patter, season and settlements classifications.





(***Note:*** **CA** – continental anticyclone, **CL** – coastal low & berg winds, **CS** – cold snap, **CutI** – cut-off low, **EL** – easterly low, **EW** – easterly wave, **RA** – ridging anticyclone, **SMF** – southerly meridional flow, **WT** – west coast trough, **WW** - westerly wave)

Figure.5.10 Box-plot showing the variability of daily averaged a) temperature (°C), b) relative humidity (%), c) wind speed ($m.s^{-1}$), d) continuous indoor PM_4 ($\mu g.m^{-3}$), e) gravimetric indoor PM_4 ($\mu g.m^{-3}$), and mean indoor PM_4 ($\mu g.m^{-3}$) within the low-income residential settlements in South Africa, categorised by the regional synoptic circulation conditions.

5.2.1. Fine-weather and mildly disturbed conditions

5.2.1.1. Continental anticyclones

5.2.1.1.1. Local meteorological conditions associated with the continental anticyclone

The continental anticyclonic circulation pattern was present for a total of four-hundred-and-two (402) days. There were a total 392, which included 40 spring, 145 summer and 217 winter, valid comparison for the ambient temperature, relative humidity (RH), and wind speed. On days presenting with the continental anticyclone synoptic circulations the observed local meteorological conditions were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged ambient temperature, relative humidity, and wind speed *(Figure.5.10)* was 14.47 (14.49) ±4.25 (6.42) [5.66-27.97] °C, 60.23 (62.81) ±16.22 (23.19) [16.17-94.58] %, and 0.87 (0.80) ±0.49 (0.97) [0.41-1.38] $m.s^{-1}$, respectively.

The seasonal temperatures were in the following order: summer > spring > winter. The summer (17.75 (17.89) ±3.16 (3.97) [10.45-26.67] °C) temperatures were 1.07 and 1.47 times higher than the spring (16.53 (16.63) ±4.15 (5.62) [8.56-27.97] °C) and winter (11.94 (11.64) ±3.06 (5.14) [5.66-18.37] °C). The seasonal relative humidity were in the following order: summer > spring > winter. The summer (39.82 (71.01) ±12.12 (14.54) [36.09-94.58] %) humidity wad 1.07 and 1.32 times higher than the spring (65.03 (64.02) ±15.90 (23.18) [36.05-91.96] %) and winter (53.07 (53.83) ±15.06 (23.17) [16.17-78.64] %). The seasonal wind speeds were in the following order: spring > summer > winter. The spring (3.23 (2.71) ±1.44 (2.23)

[0.95-6.19] $m.s^{-1}$wind speeds were 1.29 times higher than the summer (2.51 (2.39) ±1.06 (1.23) [0.00-5.54] $m.s^{-1}$) and winter (2.43 (2.33) ±1.04 (1.19) [0.10-5.47] $m.s^{-1}$).

5.2.1.1.2. Indoor PM_4 mass concentrations associated with the continental anticyclone

The continuous-, gravimetric- and combined indoor PM_4 had 357, 173, 380 valid comparisons. On days presenting with the continental anticyclone synoptic circulations the observed indoor particulate loadings were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged continuous-, gravimetric, and combined indoor PM_4 *(Figure.5.10)*was 95.16 (63.85) ±89.34 (88.73) [5.22-591.91] $\mu g.m^{-3}$, 109.12 (77.19) ±213.24 (71.46) [8.84-2014.28] $\mu g.m^{-3}$, and 110.48 (73.02) ±161.64 (83.09) [9.27-2014.28] $\mu g.m^{-3}$, respectively.

Seasonal variations in indoor PM_4 associated with the continental anticyclone

The seasonal continuous PM_4 was in the following order: spring > winter > summer. The spring (115.67 (90.84) ±95.23 (99.39) [18.82-343.10] $\mu g.m^{-3}$) concentrations were 1.05 and 1.67 times higher than the winter (110.15 (75.17) ±101.36 (112.42) [5.22-591.91] $\mu g.m^{-3}$) and summer (69.17 (53.17) ±58.43 (51.64) [7.75-470.97] $\mu g.m^{-3}$). The seasonal gravimetric PM_4 was in the following order: summer > spring > winter. The summer (136.13 (71.46) ±319.80 (46.51) [15.36-2014.28] $\mu g.m^{-3}$) concentrations were 1.10 and 1.51 times higher than the spring (124.04 $\mu g.m^{-3}$ for a single sample) and winter (89.98 (82.88) ±75.71 (82.31) [8.84-658.91] $\mu g.m^{-3}$). The seasonal combined PM_4 was in the following order: winter > spring > summer. The winter (116.72 (90.50) ±98.98 (96.87) [9.27-658.91] $\mu g.m^{-3}$) concentrations were 1.01 and 1.16 times higher than the spring (115.19 (90.84) ±95.10 (94.35) [18.82-343.10] $\mu g.m^{-3}$) and summer (100.40 (59.03) ±231.26 (51.08) [12.28-2014.28] $\mu g.m^{-3}$).

Settlement variations in indoor PM_4 associated with the continental anticyclone

The variations in the particulate loadings, associated with the continental anticyclone circulation, for each settlement is presented in *Figure.5.11.* The combined PM_4 loadings are investigated further with regard to the settlements. The mean (±SD) daily averaged ambient temperature, relative humidity, and wind speed for the individual settlements were as follow: i) ***temperature:*** Giyani (19.81 (±3.80) °C) >Agincourt (16.64 (±2.72) °C) >KwaZamokuhle (14.23 (±4.38) °C) >Jouberton (13.74 (±3.67) °C) >KwaDela (12.61 (±3.79) °C); ii) ***relative humidity:*** Giyani (69.84 (±10.85) %) > Agincourt (62.22 (±16.44) %) > KwaZamokuhle (61.34 (±16.23) %) > KwaDela (60.35 (±16.13) %) >Jouberton (49.80 (±13.50) %) > ; and ii) ***wind speed:*** KwaDela (3.09 (±0.95) $m.s^{-1}$) > KwaZamokuhle (2.63 (±2.63) $m.s^{-1}$) >Agincourt (2.56 (±0.61) $m.s^{-1}$) >Jouberton (1.72 (±0.70) $m.s^{-1}$) >Giyani (0.99 (±0.77) $m.s^{-1}$).

The mean ±SD daily averaged combined PM_4 mass concentration for the individual settlements were in the following order: KwaDela (142.61 (±248.97) µg.m^{-3}) > KwaZamokuhle (126.6 (±104.68) µg.m^{-3}) > Jouberton (78.83 (±39.11) µg.m^{-3}) > Giyani (71.66 (±61.23) µg.m^{-3}) > Agincourt (66.83 (±38.70) µg.m^{-3}).

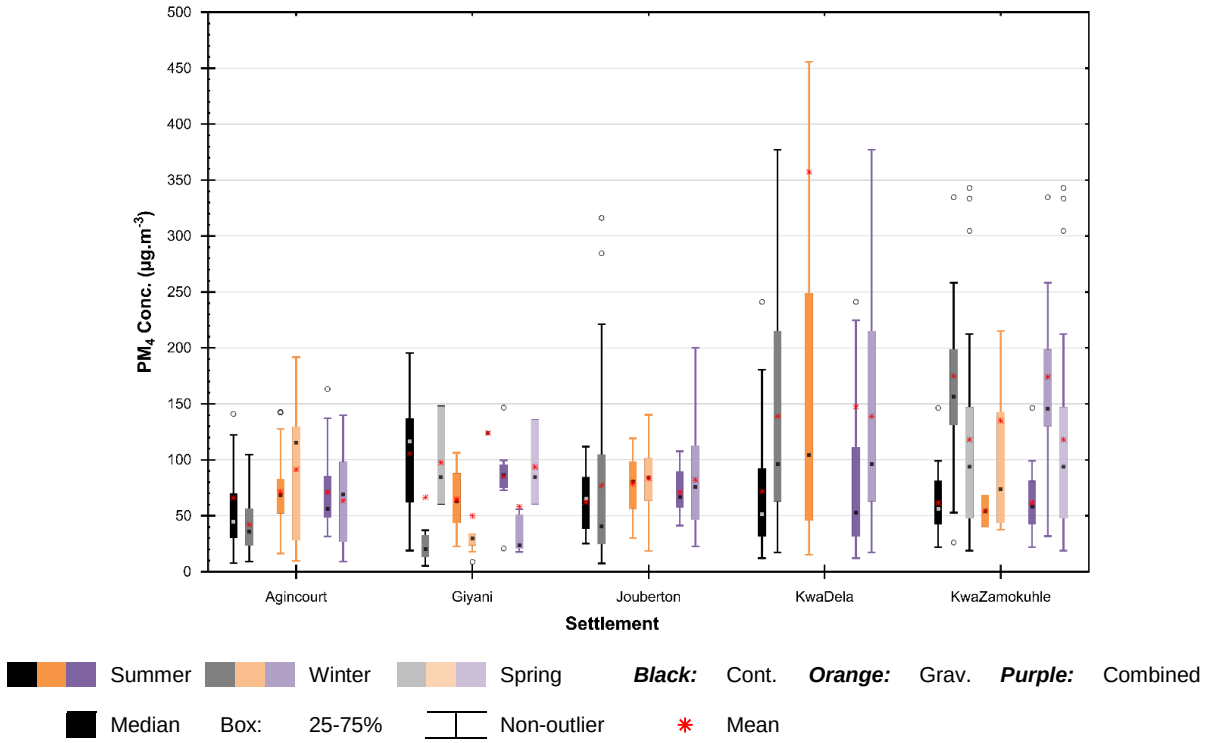


Figure.5.11 Continental anticyclones - Box-plot showing the variability of daily averaged continuous-, gravimetric-, and combined indoor PM_4 (µg.m^{-3}) within the low-income residential settlements in South Africa, categorised by the settlement and season.

Continental anticyclones are associated with adiabatic heating of the atmosphere, which results in a highly stable atmosphere. These stable conditions result in the development of inversion layers leading to low convective mixing. The low mixing inhibits the dispersion of atmospheric pollutants, resulting in longer periods of increased particulate loadings. Low wind speeds are also associated with stables conditions due to subsidence related to adiabatic heating. The low wind speeds further reduces dispersion capabilities within a localised region.

5.2.2. Tropical disturbances in the easterlies

5.2.2.1. Easterly waves

5.2.2.1.1. Local meteorological conditions associated with the easterly waves

The easterly wave circulation pattern was present for a total of four-hundred-and-two (256) days. There were a total 294, which included 36 spring, 162 summer and 58 winter, valid comparison for the ambient temperature, relative humidity (RH), and wind speed. On days presenting with the easterly wave synoptic

circulations the observed local meteorological conditions were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged ambient temperature, relative humidity, and wind speed *(Figure.5.10)* was 19.16 (18.93) ±4.06 (5.17) [6.57-31.63] °C, 62.45 (65.32) ±16.62 (22.33) [16.49-97.05] %, and 2.48 (2.48) ±1.06 (1.31) [0.05-5.63] $m.s^{-1}$, respectively.

The seasonal temperatures were in the following order: spring > summer > winter. The spring (21.45 (20.53) ±3.74 (4.35) [6.39-15.62] °C) temperatures were 1.07 and 1.46 times higher than the summer (20.13 (20.29) ±3.22 (4.63) [11.92-27.99] °C) and winter (14.67 (14.59) ±3.24 (4.35) [6.57-20.26] °C). The seasonal relative humidity were in the following order: summer > spring > winter. The summer (69.52 (69.59) ±12.52 (16.39) [21.40-97.05] %) humidity wad 1.35 and 1.43 times higher than the spring (51.45 (50.43) ±14.82 (25.36) [26.40-79.67] %) and winter (48.59 (49.54) ±16.01 (24.29) [16.49-92.54] %). The seasonal wind speeds were in the following order: spring > winter. The spring (2.75 (2.93) ±0.90 (1.29) [0.76-4.56] $m.s^{-1}$wind speeds were 1.07 and 1.15 times higher than the winter (2.56 (2.40) ±1.15 (1.38) [0.35-5.27] $m.s^{-1}$) and summer (2.39 (2.44) ±1.06 (1.31) [0.05-5.63] $m.s^{-1}$).

5.2.2.1.2. Indoor PM_4 mass concentrations associated with the easterly waves

The continuous-, gravimetric- and combined indoor PM_4 had 227, 129, and 245 valid comparisons. On days presenting with the easterly wave synoptic circulations the observed indoor particulate loadings were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged continuous-, gravimetric, and combined indoor PM_4 *(Figure.5.10)* was 78.95 (51.95) ±69.57 (72.62) [4.69-410.44] $\mu g.m^{-3}$, 140.34 (68.85) ±328.47 (47.48) [2.26-2511.33] $\mu g.m^{-3}$, and 113.37 (62.77) ±239.99 (70.66) [3.18-2511.33] $\mu g.m^{-3}$, respectively.

Seasonal variations in indoor PM_4 associated with the easterly waves

The seasonal continuous PM_4 was in the following order: spring > winter > summer. The spring (118.02 (108.98) ±79.62 (158.55) [20.46-300.38] $\mu g.m^{-3}$) concentrations were 1.14 and 1.90 times higher than the winter (103.79 (83.82) ±83.92 (143.80) [5.02-304.92] $\mu g.m^{-3}$) and summer (62.24 (45.56) ±55.08 (43.28) [4.69-410.44] $\mu g.m^{-3}$). The seasonal gravimetric PM_4 was in the following order: summer > spring > winter. The summer (156.70 (68.53) ±370.31 (41.88) [3.18-2511.33] $\mu g.m^{-3}$) concentrations were 1.11 and 1.97 times higher than the spring (141.48 $\mu g.m^{-3}$ for a 2 samples) and winter (79.67 (67.68) ±64.38 (85.76) [2.26-275.28] $\mu g.m^{-3}$). The seasonal combined PM_4 was in the following order: spring > summer > winter. The spring (118.81 (109.19) ±79.66 (158.55) [20.46-300.38] $\mu g.m^{-3}$) concentrations were 1.05 and 1.08 times higher than the summer (113.55 (55.43) ±291.50 (39.65) [3.18-2511.33] $\mu g.m^{-3}$) and winter (109.87 (88.87) ±81.34 (136.65) [5.40-304.92] $\mu g.m^{-3}$).

Settlement variations in indoor PM_4 associated with the easterly waves

The variations in the particulate loadings, associated with the easterly wave circulation, for each settlement is presented in *Figure.5.12*. The combined PM_4 loadings are investigated further with regard to the settlements.

The mean (±SD) daily averaged ambient temperature, relative humidity, and wind speed for the individual settlements were as follow: i) ***temperature:*** Giyani (24.31 (±3.74) °C) >Agincourt (20.56 (±3.16) °C) > Jouberton (19.30 (±4.08) °C) > KwaZamokuhle (17.95 (±3.77) °C) > KwaDela (17.53 (±2.59) °C); ii) ***relative humidity:*** Agincourt (70.73 (±14.29) %) > Giyani (68.70 (±12.51) %) > Jouberton (63.64 (±15.02) %) > KwaDela (62.64 (±18.29) %) > KwaZamokuhle (55.99 (±16.26) %); ***wind speed:*** KwaDela (3.13 (0.81) $m.s^{-1}$) > KwaZamokuhle (2.74 (1.00) $m.s^{-1}$) > Agincourt (2.71 (0.61) $m.s^{-1}$) > Jouberton (1.83 (0.75) $m.s^{-1}$) > Giyani (1.12 (0.76) $m.s^{-1}$).The mean ±SD daily averaged combined PM_4 mass concentration for the individual settlements were in the following order: KwaDela (193.84 (452.53) $\mu g.m^{-3}$) >Giyani (112.2 (74.51) $\mu g.m^{-3}$) >KwaZamokuhle (102.62 (70.05) $\mu g.m^{-3}$) > Agincourt (65.69 (45.32) $\mu g.m^{-3}$) >Jouberton (60.58 (57.03) $\mu g.m^{-3}$).

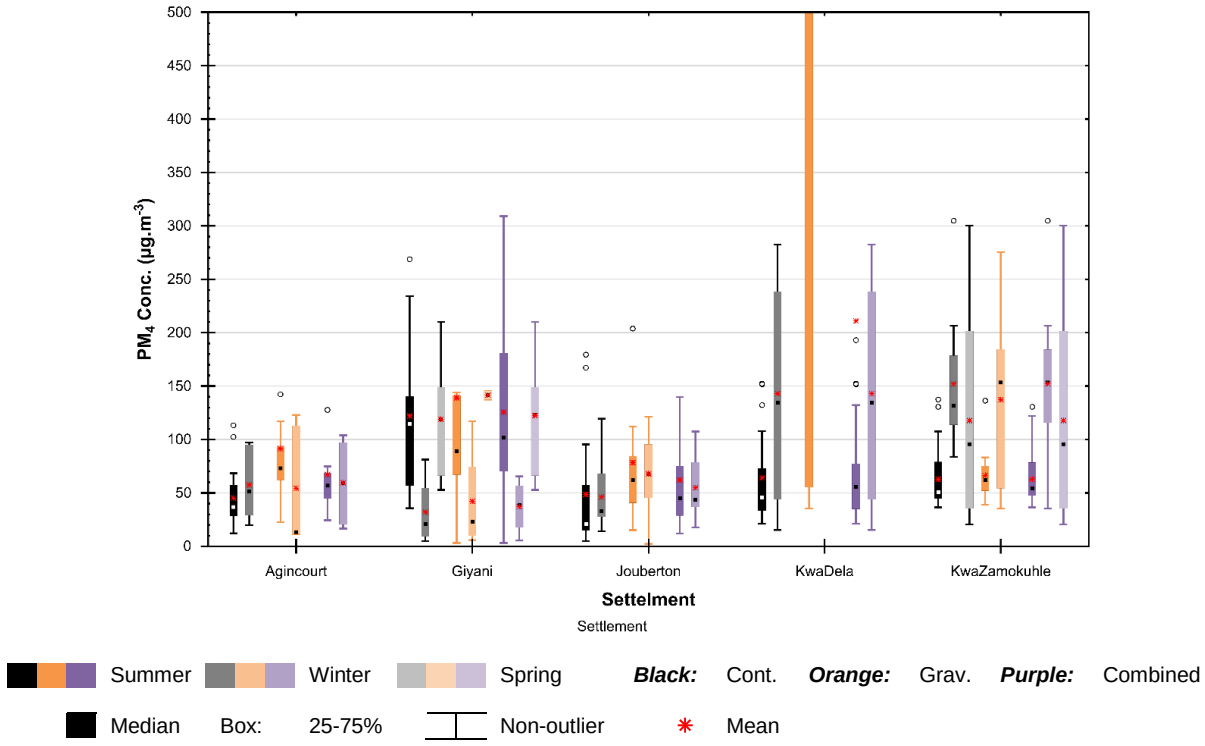


Figure.5.12 Easterly waves - Box-plot showing the variability of daily averaged continuous-, gravimetric-, and combined indoor PM_4 ($\mu g.m^{-3}$) within the low-income residential settlements in South Africa, categorised by the settlement and season.

Easterly waves are associated with more tropical weather and warmer temperatures. The local wind speeds are still fairly low with this synoptic circulation pattern, thus it has a reduced pollution dispersion potential.

5.2.3. Temperate disturbances in the westerlies

5.2.3.1. Ridging anticyclones

5.2.3.1.1. Local meteorological conditions associated with the ridging anticyclone

The ridging anticyclonic circulation pattern was present for a total of one-hundred-and-twenty-eight (128) days. There were a total 129, which included 6 spring, 50 summer and 72 winter, valid comparison for the ambient temperature, relative humidity (RH), and wind speed. On days presenting with the ridging anticyclone synoptic circulations the observed local meteorological conditions were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged ambient temperature, relative humidity, and wind speed *(Figure.5.10)* was 14.91 (15.04) ±4.50 (7.14) [4.09-24.95] °C, 57.32 (55.69) ±18.59 (29.58) [23.89-94.21] %, and 2.86 (2.74) ±1.29 (1.49) [0.25-8.02] $m.s^{-1}$, respectively.

The seasonal temperatures were in the following order: summer > spring > winter. The summer (18.40 (17.89) ±2.75 (3.49) [13.02-24.95] °C) temperatures were 1.05 and 1.51 times higher than the spring (17.53 (18.24) ±2.36 (4.36) [4.36-14.56] °C) and winter (12.22 (11.80) ±3.75 (4.56) [4.09-21.10] °C). The seasonal relative humidity were in the following order: summer > spring > winter. The summer (71.88 (72.35) ±12.24 (22.19) [52.14-94.21] %) humidity was 1.19 and 1.54 times higher than the spring (60.37 (60.96 ±10.73 (19.59) [45.53-72.00] %) and winter (46.78 (43.06) ±15.64 (20.15) [23.89-83.40] %). The seasonal wind speeds were in the following order: spring > winter > summer. The spring (3.42 (3.21) ±0.94 (1.53) [2.34-4.78] $m.s^{-1}$wind speeds were 1.14 and 1.31 times higher than the winter (2.99 (2.80) ±1.49 (1.91) [0.25-8.02] $m.s^{-1}$) and summer (2.62 (2.65) ±0.95 (1.04) [0.48-5.47] $m.s^{-1}$).

5.2.3.1.2. Indoor PM_4 mass concentrations associated with the ridging anticyclone

The continuous-, gravimetric- and combined indoor PM_4 had 113, 61, and 124 valid comparisons. On days presenting with the ridging anticyclone synoptic circulations the observed indoor particulate loadings were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged continuous-, gravimetric, and combined indoor PM_4 *(Figure.5.10)* was 79.67 (49.19) ±85.48 (62.76 [8.84-418.05] $\mu g.m^{-3}$, 91.44 (70.53) ±120.09 (49.25) [5.63-889.18] $\mu g.m^{-3}$, and 95.01 (60.73) ±110.84 (59.97) [7.42-889.18] $\mu g.m^{-3}$, respectively.

Seasonal variations in indoor PM_4 associated with the ridging anticyclone

The seasonal continuous PM_4 was in the following order: spring > winter > summer. The spring (158.66 (166.80) ±118.61 (235.96) [32.04-275.38] $\mu g.m^{-3}$) concentrations were 1.86 and 2.67 times higher than the winter (85.40 (52.52) ±95.28 (74.14) [9.21-418.05] $\mu g.m^{-3}$) and summer (59.51 (43.27) ±51.89 (35.62) [8.84-243.10] $\mu g.m^{-3}$). The seasonal gravimetric PM_4 was in the following order: summer > winter. The summer (103.27 (77.09) ±164.96 (21.18) [20.57-889.18] $\mu g.m^{-3}$) concentrations were 1.24 times higher

than the winter (83.22 (60.93) ±76.78 (65.29) [5.63-409.66] µg.m^{-3}). The seasonal combined PM_4 was in the following order: spring > winter > summer. The spring concentrations were 1.62 and 1.92 times higher than the winter (97.98 (64.69) ±96.89 (77.87) [7.42-418.305] µg.m^{-3}) and summer (82.72 (59.24) ±127.22 (30.65) [20.57-889.18] µg.m^{-3}).

Settlement variations in indoor PM_4 associated with the ridging anticyclone

The variations in the particulate loadings, associated with the ridging anticyclone synoptic circulation, for each settlement is presented in *Figure.5.13*. The combined PM_4 loadings are investigated further with regard to the settlements. The mean (±SD) daily averaged ambient temperature, relative humidity, and wind speed for the individual settlements were as follow: i) ***temperature:*** Giyani (20.55 (3.07) °C) >Agincourt (17.06 (2.85)) °C) > Jouberton (14.46 (3.67) °C) > KwaZamokuhle (14.17 (5.01) °C) > KwaDela (13.61 (4.45) °C); ii) ***relative humidity:*** Giyani (71.60 (13.83) %) > Agincourt (62.84 (19.91) %) > KwaDela (57.50 (20.56) %) > KwaZamokuhle (56.90 (15.14) %) > Jouberton (50.16 (17.11) %); ***wind speed:*** KwaDela (3.65 (1.20) m.s^{-1}) > KwaZamokuhle (2.90 (1.46) m.s^{-1}) > Agincourt (2.67 (0.63) m.s^{-1}) > Jouberton (2.48 (0.90) m.s^{-1}) > Giyani (0.94 (0.51) m.s^{-1}).

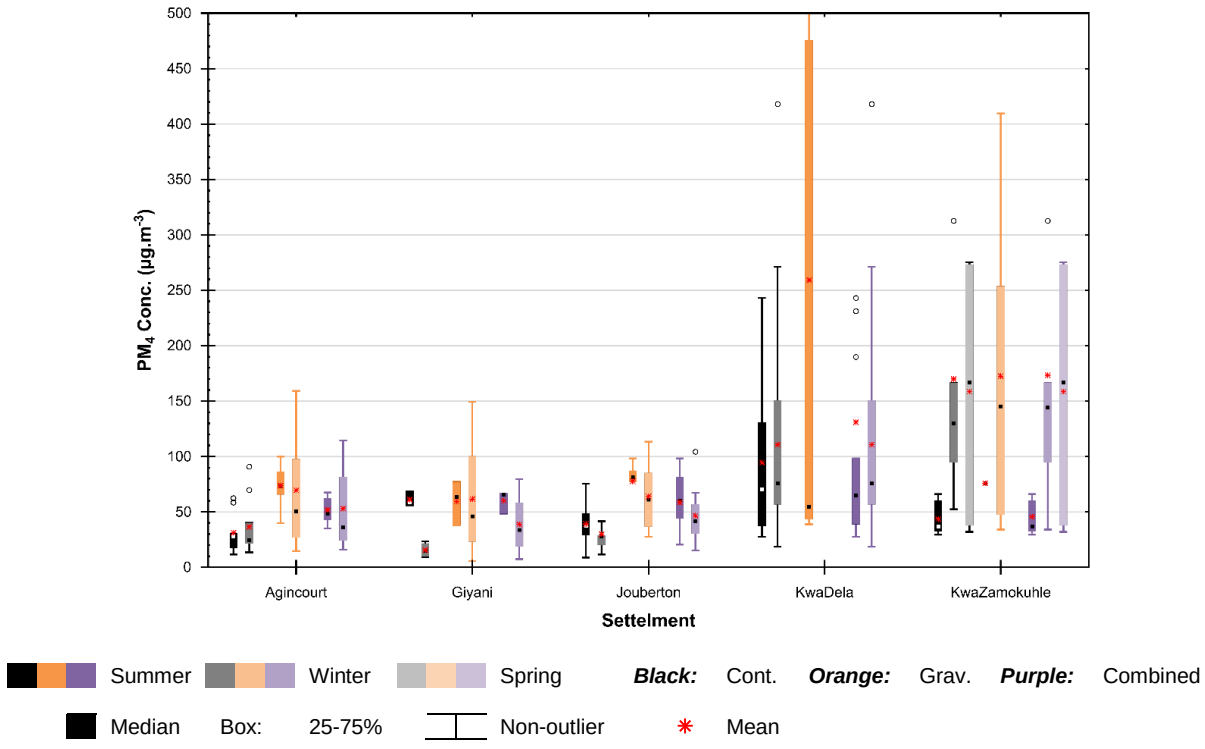


Figure.5.13 Ridging anticyclone - Box-plot showing the variability of daily averaged continuous-, gravimetric-, and combined indoor PM_4 (µg.m^{-3}) within the low-income residential settlements in South Africa, categorised by the settlement and season.

The mean ±SD daily averaged combined PM_4 mass concentration for the individual settlements were in the following order: KwaZamokuhle (140.69 (118.58) µg.m^{-3}) >KwaDela (119.93 (150.45) µg.m^{-3}) > Agincourt (52.48 (26.25) µg.m^{-3}) > Jouberton (51.15 (22.10) µg.m^{-3}) > Giyani (47.93 (24.95) µg.m^{-3}).

5.2.3.2. Cut-off lows

5.2.3.2.1. Local meteorological conditions associated with the cut-off lows

The cut-off low circulation pattern was present for a total of eighty-eight (88) days. There were a total 88, which included 13 spring, 24 summer and 51 winter, valid comparison for the ambient temperature, relative humidity (RH), and wind speed. On days presenting with the cut-off low synoptic circulations the observed local meteorological conditions were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged ambient temperature, relative humidity, and wind speed *(Figure.5.10)* was 16.03 (16.02) ±4.49 (6.88) [6.20-26.10] °C, 53.16 (52.08) ±19.02 (34.19) [16.00-94.05] %, and 3.18 (3.24) ±1.32 (1.53) [0.05-6.57] m.s^{-1}, respectively.

The seasonal temperatures were in the following order: spring > summer > winter. The spring (19.86 (20.06) ±3.69 (2.85) [11.66-26.10] °C) temperatures were 1.07 and 1.46 times higher than the summer (18.49 (17.85) ±10.83 (26.07) [16.00-20.41] °C) and winter (13.59 (14.36) ±3.53 (5.64) [6.20-20.57] °C). The seasonal relative humidity were in the following order: summer > spring > winter. The summer (71.28 (74.30) ±46.05 (94.05) [59.08-79.75] %) humidity wad 1.43 and 1.62 times higher than the spring (49.82 (49.39) ±46.05 (16.39) [27.82-79.73] %) and winter (43.98 (43.71) ±15.22 (21.87) [16.00-79.73] %). The seasonal wind speeds were in the following order: winter > spring > summer. The winter (3.35 (3.24) ±1.48 (2.33) [0.41-6.57] m.s^{-1}) wind speeds were 1.02 and 1.19 times higher than the spring (3.28 (3.52) ±0.95 (1.16) [1.77-5.08] m.s^{-1}) and summer (2.82 (2.88) ±0.05 (4.49) [2.18-3.72] m.s^{-1}).

5.2.3.2.2. Indoor PM_4 mass concentrations associated with the cut-off lows

The continuous-, gravimetric- and combined indoor PM_4 had 75, 30, and 80 valid comparisons. On days presenting with the cut-off low synoptic circulations the observed indoor particulate loadings were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged continuous-, gravimetric, and combined indoor PM_4 *(Figure.5.10)* was 98.21 (58.79) ±87.81 (116.99) [9.24-335.26] µg.m^{-3}, 125.86 (79.01) ±180.95 (86.17) [15.15-974.89] µg.m^{-3}, and 115.27 (65.35) ±133.56 (120.47) [14.96-974.89] µg.m^{-3}, respectively.

Seasonal variations in indoor PM_4 associated with the cut-off lows

The seasonal continuous PM_4 was in the following order: spring > winter > summer. The spring (118.06 (105.55) ±92.15 (145.26) [23.44-283.02] $\mu g.m^{-3}$) concentrations were 1.16 and 1.56 times higher than the winter (104.36 (64.66) ±92.84 (125.22) [9.24-335.26] $\mu g.m^{-3}$) and summer (75.81 (49.09) ±13.48 (288.47) [33.42-83.06] $\mu g.m^{-3}$). The seasonal gravimetric PM_4 was in the following order: summer > winter. The summer (173.87 (72.98) ±21.39 (245.74) [56.43-974.89] $\mu g.m^{-3}$) concentrations were 1.71 times higher than winter (104.36 (64.66) ±92.84 (125.22) [9.24-335.26] $\mu g.m^{-3}$). The seasonal combined PM_4 was in the following order: spring > summer > winter. The spring concentrations were 1.02 and 1.03 times higher than the summer (116.29 (58.31) ±22.80 (147.02) [36.69-974.89] $\mu g.m^{-3}$) and winter (114.33 (71.33) ±100.09 (123.92) [14.96-416.52] $\mu g.m^{-3}$).

Settlement variations in indoor PM_4 associated with the cut-off lows

The variations in the particulate loadings, associated with the cut-off low synoptic circulation, for each settlement is presented in *Figure.5.14*. The combined PM_4 loadings are investigated further with regard to the settlements. The mean (±SD) daily averaged ambient temperature, relative humidity, and wind speed for the individual settlements were as follow: i) ***temperature:*** Giyani (21.57 (5.07) °C) >Agincourt (18.62 (2.94)) °C) > KwaZamokuhle (16.46 (5.06) °C) > KwaDela (14.45 (3.38) °C) > Jouberton (11.70 (4.13) °C) >; ii) ***relative humidity:*** Giyani (66.23 (12.24) %) > KwaDela (53.93 (20.53) %) > Jouberton (53.60 (25.03) %) > KwaZamokuhle (51.96 (16.50) %) >Agincourt (49.36 (20.27) %); ***wind speed:*** KwaDela (4.14 (1.06) $m.s^{-1}$) > KwaZamokuhle (2.76 (0.97) $m.s^{-1}$) > Agincourt (2.62 (0.44) $m.s^{-1}$) > Jouberton (2.41 (0.77) $m.s^{-1}$) > Giyani (0.36 (0.33) $m.s^{-1}$).

The mean ±SD daily averaged combined PM_4 mass concentration for the individual settlements were in the following order: KwaZamokuhle (147.63 (101.18) $\mu g.m^{-3}$) >KwaDela (120.59 (175.11) $\mu g.m^{-3}$) > Giyani (93.44 (99.60) $\mu g.m^{-3}$) >Agincourt (75.83 (42.39) $\mu g.m^{-3}$) > Jouberton (49.23 (29.56) $\mu g.m^{-3}$).

Cut-off lows are associated with unstable atmospheric condition which could result in the formation of clouds and thus possible precipitation. It can also result in a surface front that could lead to a fall in temperatures. These lows are characterised by stronger surface winds. These synoptic circulation patterns would result in conditions that could lead to large variability in particulate loadings. It could also enhance the use of solid fuels for space heating, along with processes that might lead to higher dispersion of ambient particulate matter.

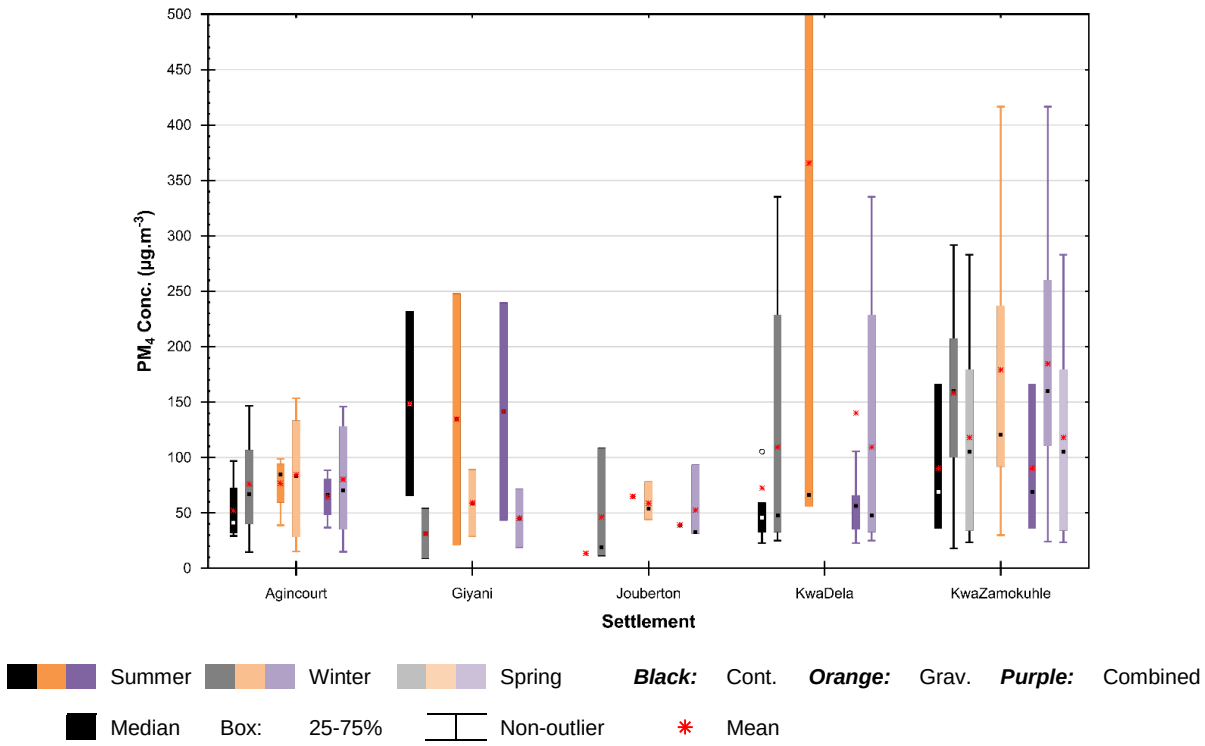


Figure.5.14 Cut-off lows - Box-plot showing the variability of daily averaged continuous-, gravimetric-, and combined indoor PM_4 ($\mu g.m^{-3}$) within the low-income residential settlements in South Africa, categorised by the settlement and season.

5.2.3.3. Westerly waves

5.2.3.3.1. Local meteorological conditions associated with the westerly waves

The westerly wave circulation pattern was present for a total of thirty-one (31) days. There were a total 31, which included 1 spring, 111 summer and 19 winter, valid comparison for the ambient temperature, relative humidity (RH), and wind speed. On days presenting with the westerly waves synoptic circulations the observed local meteorological conditions were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged ambient temperature, relative humidity, and wind speed *(Figure.5.10)* was 16.02 (16.08) ±3.86 (5.96) [10.12-23.14] °C, 51.00 (48.88) ±13.94 (17.71) [27.22-88.33] %, and 2.85 (2.51) ±1.18 (1.47) [0.33-5.96] $m.s^{-1}$, respectively. Due to the small sample size, the single spring sample is excluded.

The seasonal temperatures were in the following order: summer > winter. The summer (19.35 (19.35) ±2.94 (4.11) [13.27-23.14] °C) temperatures were 1.41 times higher than the winter (13.76 (13.68) ±2.40 (3.97) [10.12-17.81] °C). The seasonal relative humidity were in the following order: summer > winter. The summer (59.01 (55.19) ±16.87 (27.00) [33.50-88.33] %) humidity was 1.25 times higher than the winter (47.10 (46.95) ±9.98 (15.44) [27.22-65.21] %). The seasonal wind speeds were in the following order: winter > summer. The winter (3.07 (3.25) ±1.40 (1.81) [0.33-5.96] $m.s^{-1}$) wind speeds were 1.18 times higher than the summer (2.59 (2.51) ±0.59 (0.82) [1.69-3.67] $m.s^{-1}$).

5.2.3.3.2. Indoor PM_4 mass concentrations associated with the westerly waves

The continuous-, gravimetric- and combined indoor PM_4 had 28, 14, and 30 valid comparisons. On days presenting with the westerly waves synoptic circulations the observed indoor particulate loadings were as follow: The mean (median) ±SD (IQR) [minimum-maximum] daily averaged continuous-, gravimetric, and combined indoor PM_4 *(Figure.5.10)* was 99.08 (47.27) ±145.81 (51.13) [21.94-742.79] $\mu g.m^{-3}$, 120.55 (87.98) ±78.15 (63.42) [39.62-318.08] $\mu g.m^{-3}$, and 111.52 (63.52) ±138.29 (71.70) [27.87-742.79] $\mu g.m^{-3}$, respectively.

Seasonal variations in indoor PM_4 associated with the westerly waves

The seasonal continuous PM_4 was in the following order: winter > summer. The winter (85.32 (59.15) ±76.34 (66.10) [21.94-305.89] $\mu g.m^{-3}$) concentrations were 1.41 times higher than the summer (60.57 (38.23) ±72.75 (18.80) [26.35-277.36] $\mu g.m^{-3}$). The seasonal gravimetric PM_4 was in the following order: winter > summer. The winter (138.65 (119.92) ±86.69 (77.31) [39.62-318.08] $\mu g.m^{-3}$) concentrations were 1.84 times higher than the summer (75.30 (76.41) ±9.68 (12.13) [62.45-85.95] $\mu g.m^{-3}$). The seasonal combined PM_4 was in the following order: winter > summer. The winter (104.17 (87.49) ±69.28 (108.66) [30.31-305.89] $\mu g.m^{-3}$) concentrations were 1.57 times higher than the summer (66.15 (48.62) ±71.37 (31.45) [27.87-277.36] $\mu g.m^{-3}$).

Settlement variations in indoor PM_4 associated with the westerly waves

The variations in the particulate loadings, associated with the westerly wave synoptic circulation, for each settlement is presented in *Figure.5.15*. The combined PM_4 loadings are investigated further with regard to the settlements. The mean (±SD) daily averaged ambient temperature, relative humidity, and wind speed for the individual settlements were as follow: i) ***temperature:*** Agincourt (19.42 (2.91) °C) > KwaZamokuhle (17.52 (3.81) °C) > Jouberton (13.74 (0.82) °C) > KwaDela (12.82 (2.30) °C); ii) ***relative humidity:*** KwaZamokuhle (54.19 (13.02) %) >Agincourt (51.82 (14.72) %) > Jouberton (52.23 (4.46) %) > KwaDela (45.83 (17.13) %); ***wind speed:*** KwaDela (4.12 (0.91) $m.s^{-1}$) > Agincourt (2.61 (0.37) $m.s^{-1}$) > Jouberton (2.50 (0.97) $m.s^{-1}$) >KwaZamokuhle (2.01 (0.43) $m.s^{-1}$).

The mean ±SD daily averaged combined PM_4 mass concentration for the individual settlements were in the following order: KwaZamokuhle (161.74 (241.37) $\mu g.m^{-3}$) >KwaDela (109.14 (106.69) $\mu g.m^{-3}$) > Agincourt (95.90 (47.60) $\mu g.m^{-3}$) > Jouberton (81.87 (45.03) $\mu g.m^{-3}$).

Similar to the cut-off lows, the westerly waves are associated with cold conditions that could also enhance the use of solid fuel for space heating activities.

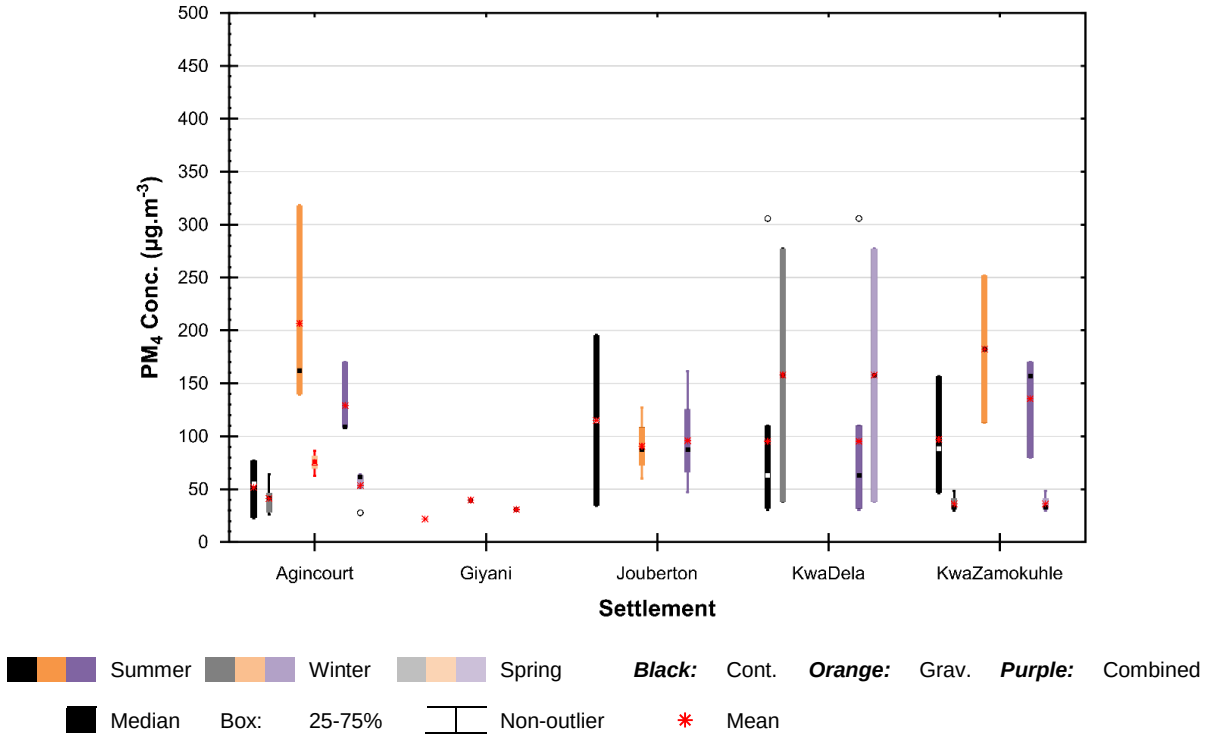


Figure.5.15 Westerly waves - Box-plot showing the variability of daily averaged continuous-, gravimetric-, and combined indoor PM_4 ($\mu g.m^{-3}$) within the low-income residential settlements in South Africa, categorised by the settlement and season.

Synoptic circulation vs indoor PM_4 mass concentrations

From the above analysis it can be seen that on average the combined indoor PM_4 within the residential low income communities, classified by the synoptic circulation was in the following order: cut-off lows (CUTL) > easterly waves (EW) > westerly waves (WW) > continental anticyclones (CA) > ridging anticyclones (RA). The indoor PM_4 mass concentrations were close to unity for the CUTL, EW, WW, and CA, while the CUTL (115.27 (±133.56) $\mu g.m^{-3}$) were a factor of 1.21 higher than the RA. There were high level of seasonal variability as well. For spring the indoor PM_4 loading was highest for the ridging anticyclone (158.66 (±118.61) $\mu g.m^{-3}$) circulation. It was on average 1.34 times higher than the EW, CUTL, and CA synoptic circulations. During summer, the cut-off lows had the highest indoor PM_4 loading, at 116.29 (±198.71) $\mu g.m^{-3}$. This was on average between and 1.02 and 1.76 times higher than the EW, CA, RA, and WW. During winter, the continental anticyclone had the highest indoor PM_4 loading at 116.72 (±98.98) $\mu g.m^{-3}$. It was on average between 1.02 and 1.19 times higher than the CUTL, EW, WW, and RA circulations.

The winter showed less variation of indoor PM4 with changing synoptic circulation patterns compared to spring and summer.

Settlement variations of synoptic circulation vs indoor PM_4 mass concentrations

In KwaDela the highest mean indoor PM_4 is associated with the easterly wave circulation (193.84 (±452.53) $\mu g.m^{-3}$). This was on average between and 1.36 and 1.78 times higher than the CA, CUTL, RA, and WW. During summer, the easterly wave circulation had the highest indoor PM_4 loading, at 211.11 (±520.92) $\mu g.m^{-3}$. This was on average between and 1.34 and 1.61 times higher than the WW, CA, CUTL, and RA. During winter, the easterly waves had the highest indoor PM_4 loading at 143.12 (±103.01) $\mu g.m^{-3}$. It was on average between 1.03 and 1.50 times higher than the CA, RA, CL, and WW circulations.

In KwaZamokuhle the highest mean indoor PM_4 is associated with the westerly wave circulation (161.74 (±241.37) $\mu g.m^{-3}$). This was on average between and 1.34 and 1.58 times higher than the CUTL, RA, CA, and EW. During spring, the ridging anticyclone circulation had the highest indoor PM_4 loading, at 158.66 (±118.61) $\mu g.m^{-3}$. This was on average between and 1.34 and 1.35 times higher than the CA, CUTL, and EW. During summer, the cut-off low circulation had the highest indoor PM_4 loading, at 90.49 (±47.19) $\mu g.m^{-3}$. This was on average between and 1.44 and 2.51 times higher than the EW, CA, RA, and WW. During winter, the cut-off lows had the highest indoor PM_4 loading at 184.71 (±107.06) $\mu g.m^{-3}$. It was on average between 1.06 and 1.36 times higher than the CA, RA, EW, and WW circulations.

In Jouberton the highest mean indoor PM_4 is associated with the westerly wave circulation (95.90 (±47.60) $\mu g.m^{-3}$) $\mu g.m^{-3}$). This was on average between and 1.23 and 1.95 times higher than the CA, EW, RA, and CUTL. During summer, the continental anticyclone circulation had the highest indoor PM_4 loading, at 71.04 (±21.03) $\mu g.m^{-3}$. This was on average 1.14 and 1.21 times higher than the EW and RA. During winter, the westerly waves had the highest indoor PM_4 loading at 95.90 (±47.60) $\mu g.m^{-3}$. It was on average between 1.17 and 2.06 times higher than the CA, EW, CUTL, and RA circulations.

In Agincourt the highest mean indoor PM_4 is associated with the westerly wave circulation (81.87 (±45.03) $\mu g.m^{-3}$). This was on average between and 1.08 and 1.56 times higher than the CUTL, CA, EW, and RA. During summer, the continental anticyclone circulation had the highest indoor PM_4 loading, at 71.07 (±42.76) $\mu g.m^{-3}$. This was on average between and 1.05 and 1.38 times higher than the EW, CUTL, WW, and RA. During winter, the westerly waves had the highest indoor PM_4 loading at 129.12 (±35.73) $\mu g.m^{-3}$. It was on average between 1.61 and 2.43 times higher than the CUTL, CA, EW, and RA circulations.

In Giyani the highest mean indoor PM_4 is associated with the easterly wave circulation (112.22 (±74.51) $\mu g.m^{-3}$). This was on average between and 1.20 and 2.39 times higher than the CUTL, CA. and RA. During spring, the easterly wave circulation had the highest indoor PM_4 loading, at 122.35 (±52.58) $\mu g.m^{-3}$. This was 1.31 times higher than the CA. During summer, the cut-off low circulation had the highest indoor PM_4 loading, at 141.61 (±138.27) $\mu g.m^{-3}$) $\mu g.m^{-3}$. This was on average between and 1.13 and 2.35 times higher than the EW, CA, and RA. During winter, the continental anticyclone had the highest indoor PM_4 loading at 58.20 (±76.15) $\mu g.m^{-3}$. It was on average between 1.29 and 1.57 times higher than the CUTL, RA, and EW circulations.

Based on the above mentioned it can be concluded that there is no district direct association between the observed synoptic circulation pattern and the indoor PM_4 mass concentration loadings. The assumption is made that the link lies between the manner in which the synoptic circulation impacts on the local meteorology (temperature, wind speed, relative humidity etc.) and how these preserved chances in return affect the behaviour of people residing in the low-income settlements. Further investigation is needed on how the synoptic circulation patterns impact on the ambient particulate levels in these communities, and what the associated indoor to outdoor particulate relationship is. Through this type of analysis direct link between synoptic scale circulation and indoor particulate loadings might be established.

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In this chapter, the characteristic of the meteorological phenomena affecting the individual settlements (KwaDela, KwaZamokuhle, Jouberton, Agincourt, and Giyani) situated within the Highveld- and Lowveld regions of the study area were discussed. This included the synoptic-scale circulation, local wind fields, temperature and relative humidity which prevailed during the various spring, summer, and winter sampling periods. It is concluded that the sampling campaigns included, both in the Highveld and Lowveld regions, in the study are representative of the typical meteorological conditions experienced in South Africa during spring, summer, and winter periods. The relationship between the observed synoptic circulation, local meteorological condition and measured indoor PM_4 mass concentrations was investigated. The following chapter addresses the summarisation of the main findings and concluding remarks.

CHAPTER 6: SUMMARY AND CONCLUSION

The study aimed to evaluate the state of respirable particulate matter within the indoor environment of low-income residential settlements, in South Africa, across various spatial and temporal resolutions. The study area was situated over the Highveld- and Lowveld regions of South Africa and included various coal burning- (KwaDela and KwaZamokuhle), urbanised- (Jouberton), and wood-burning (Agincourt and Giyani) communities. A number of important findings have emerged from this study. These findings, as they pertain to each research objective outlined in *Chapter 1, Section 1.4*, are summarised in this chapter.

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6.1. Summary of the main findings of the study

6.1.1. Field evaluation of photometric instruments

Objective I: *Evaluate the use of photometric particulate monitors within the indoor environment of low-income residential settlements in South Africa*.

The objective was addressed through the use of three collocated evaluation studies as described in *Chapter 2, Section 0*. The results and discussion surrounding this objective were presented in *Chapter 3*. The main findings for each sub-objective are as follow:

6.1.1.1. Photometric calibration factors (PCFs)

(1) Residential indoor PM_4 mass concentrations are both over- and underestimated by the continuous photometric instruments.

(2) The overestimation of residential indoor PM_4 mass concentration is more prevalent during the winter, regardless of the community, settlement, household fuels use, and instrument classification.

(3) The underestimation of residential indoor PM_4 mass concentration mainly occurs during spring and summer, and more so in the wood-burning communities than in the coal-burning- or urbanised settlements.

(4) Mean residential indoor PM_4 PCFs were calculated for the various categories of classification (community type, settlement, season, household fuel use, and instruments model), it was as

follow, i) ***community:*** coal-burning (0.66), urban (0.61), and wood-burning (1.64); ii) ***settlement:*** KwaDela (0.47), KwaZamokuhle (0.76), Jouberton (0.61), Agincourt (1.55), and Giyani (1.72); iii) ***season:*** spring (1.18), summer (1.50), and winter (0.65); iv) ***household fuel use:*** ISFB (0.66), NSFB (1.36), and OSFB (1.61); and v) ***instrument model:*** DT (0.66), DTII (1.29), and SP (0.83). However, due to the high variability within each classification, the application of these PCFs could result in over- or under corrected values. This holds implications for using generalised PCFs to a community or even similar communities within the same region. This emphasises the importance of calculating PCFs for specific micro-environments.

(5) Twenty-nine (29) individual residential indoor PM_4 PCFs were calculated based on the community type, settlement, season, household solid fuel use, and instrument model *(see Chapter 3, Section 3.1.2, Table 3.1)*. The mean PM_4 PCF was 1.09, however, when this is separated by over- and underestimation the mean PCFs are 0.53 and 2.15, respectively.

(6) The residential indoor PM_4 PCFs calculated to correct specifically for overestimation by the photometric instruments are within the range of other $PM_{2.5}$ and PM_{10} PCFs reported in the literature, however, this study included mean cases of underestimation which were not present in the literature.

(7) While it is unlikely that the exact same PCFs presented in this study could be applied in other indoor studies given high variability that exists from site-to-site, which highlight the importance of quantifying PCFs and provides guidance for other studies using photometric instruments to measure particulate matter within the residential indoor environment.

6.1.1.2. Photometric instrument comparability

(8) There are significant differences in the uncorrected initial indoor PM_4 mass concentrations measured by the various photometric instrument models. The summer instrument measurements were more comparable than those recorded during winter. These differences can be linked back to the level of over- and underestimation by the instruments.

(9) The comparability of different instrument models improved between 15 and 46% with the application of instrument-specific PCFs that were calculated for the specific micro-environment. This supports the use of specific PCFs over a mean PCF.

(10) The PM_4 mass concentrations from the different DT, DTII and SP photometric instrument models are comparable if, and only if, the appropriate PCFs are used to correct for any possible over- or underestimations of the mass concentrations.

(11) The importance of proper factory-, flow-, and zero calibrations are emphasised as these impacts on the comparability of measurements obtained from different model instruments.

6.1.1.3. Size-fractionation of indoor particulate matter

(12) The ultrafine (PM_1) fraction could be influenced more by instrument artefacts compared to the PM_{10}, PM_4, and $PM_{2.5}$.

(13) The PM_{10}, PM_4, and $PM_{2.5}$ measurements are closely related with higher variability in its relationship to PM_1.

(14) PM_4 mass concentrations measurements can be accurately converted to $PM_{2.5}$ by applying a conversion factor of 0.92 facilitating comparisons with international studies, health outcomes, and existing $PM_{2.5}$ NAAQS and WHO guidelines.

(15) The respirable particle fraction (PM_4) contributes to ~93% of total PM_{10}.

(16) The fine particle fraction ($PM_{2.5}$) contributes to ~82% of total PM_4.

(17) The ultrafine particle fraction (PM_1) contributes to ~70% of total $PM_{2.5}$.

(18) The bulk of suspended particulate matter present in the residential indoor environment is of the respirable-size fraction or smaller.

6.1.2. Characterisation and source identification of indoor PM_4

Objective II: *Assess the status of indoor air quality with respect to the mass concentration of respirable particulate matter (PM_4) within the indoor environment of low-income residential settlements in South Africa.*

The objective was addressed through the use of continuous particle monitoring as described in *Chapter 2, Section 2.3.2.1*. The results and discussion surrounding this objective were presented in *Chapter 4, Section 4.1.1*. The main findings for each sub-objective were as follow:

6.1.2.1. Continuous residential indoor PM_4 mass concentrations

(19) The five settlements samples in this study experienced poor indoor air quality associated specifically with the respirable particle fraction. The low-income settlement had a mean (±SD) PM_4 loading of 116 (±357) $\mu g.m^{-3}$.

(20) Coal-burning (137 (±403) $\mu g.m^{-3}$) communities experienced mean indoor PM_4 loadings which were 2.59 to 2.53 times higher than the urbanised- (53 (±171) $\mu g.m^{-3}$) and wood-burning (58 (±143) $\mu g.m^{-3}$) communities.

- These populations could therefore experience higher levels of negative health impacts, such as respiratory infections, associated with increased particulate loadings.

(21) There are definite variations in the residential indoor PM_4 loadings measured within the individual settlements. KwaDela had the highest mean (±SD) PM_4 loading with 154 (±480)

$\mu g.m^{-3}$. The concentration in this settlement was a factor of 1.34 higher than its neighbouring coal-burning settlement of KwaZamokuhle. It was a factor of 2.63 higher in the urban community of Jouberton. KwaDela particulate loadings were also 3.03 and 1.88 times higher than the wood-burning communities of Agincourt and Giyani.

- Difference could be attributed to the level of indoor solid fuel combustion activities occurring within the households. Thus, the assumption is made that residents within KwaDela might be burning more consistently throughout the year compared to KwaZamokuhle.

(22) Spring PM_4 loading in KwaZamokuhle was a factor of 1.13 higher than Giyani.

(23) Summer had higher PM_4 variability for the individual settlements. This variability makes it difficult to form assumptions about which type of community will experience higher indoor particle loadings. The settlements were in the following order: KwaDela > Giyani > KwaZamokuhle > Agincourt > Jouberton. The particulate loadings in KwaDela were higher by factors ranging between 1.67 and 3.65.

(24) Winter PM_4 loadings, for the individual settlements, conformed to the expected as KwaDela > KwaZamokuhle > Urban > Giyani > Agincourt. The particulate loadings in KwaDela were higher by factors ranging between 1.25 and 3.3, thus showing slightly less variation than during the summer.

(25) Based on the household fuel use classification, the mean PM_4 loading was as follow: ISFB > NSFB > OSFB. The ISFB dwelling experienced particulate loadings 2.39 and 2.48 times higher than NSFB and OSFB households. This is also true for summer and winter. There was a higher difference between the household for winter.

(26) The individual households had very high intra- and inter-household variability of PM_4 loadings, regardless of the community, settlement, season, or fuel use classification.

- The variations within settlements could possibly be influenced by residential solid fuel burning practices (in rural areas burning is frequently conducted outdoors in a designated cooking area) as well as the proximity dwellings to one another. The potential for infiltration to take place through open doors and windows is higher in urban townships.

6.1.2.2. Diurnal patterns of continuous residential indoor PM_4 mass concentrations

(27) A district bi-modal diurnal pattern was observed for hourly averaged PM_4 within the residential indoor environment of low-income communities in South Africa. The peaks occur during the morning and evening and usually coincide with increased domestic solid fuel

combustion- and road traffic activities. These periods of increased particulate loading can last anywhere between one and nine hours.

(28) The bi-modal diurnal pattern was observed within the coal-burning-, urbanised, and wood-burning communities for all seasons (spring, summer and winter). The spring and winter patterns are more pronounced than that of the summer.

(29) The fuel use classification is also significant, as the ISFB dwellings typically have increased indoor PM_4 loadings compared to the NSFB- and OSFB. This can be observed in the difference seen within the ISFB peaks, which are two to four-time higher than the NSFB and OSFB households.

- Residents within the ISFB households are exposed to higher levels of particulate pollution for longer periods than the occupant of NSFB dwellings. The extended periods of extreme exposure could lead to increased occurrences of various health impacts.
- Urbanised- and wood-burning communities have increased variations between the ISFB-, NSFB-, and OSFB dwellings compared to the coal-burning communities: i) higher ambient loading of particulate matter results in a reduced difference between the indoor PM_4 loadings; and ii) in communities where solid fuel burning is not prevalent, the impact of burning activities in households could proportionally have a significant impact on those residents compared to the coal-burning communities.

(30) The evening peaks are also more pronounced than the morning as it can be one to three times higher than corresponding morning peaks.

(31) The peaks are initiated earlier in the households that are primary sources of PM_4, like the ISFB. This further links indoor solid fuel-burning the indoor PM_4 in households that do not burn solid fuel.

(32) The indoor PM_4 diurnal pattern is mostly influenced by activities which occur within or around the residence, as well as activities within the broader settlements itself.

6.1.2.3. Daytime and nighttime variability of continuous residential indoor PM_4 mass concentrations

(33) In the residential indoor environment, the night-time (18h00 to 06h00) PM_4 loadings were slightly higher, by a factor of 1.09 (±1.1) than the day-time (07h00 to 17h00) measurements. The day-time showed higher variation between the ISFB, NSFB and OSFB dwellings than during the night.

(34) There are more extreme (higher maximum) concentrations recorded during the night. The night-time maximums in the ISFB, NSFB, and OSFB were factors of i) spring: 3.50, 2.97, and

1.45; ii) summer: 1.08, 7.73, and 3.55; while iii) winter: shows less variability than spring and summer.

6.1.2.4. Exceedances of the 24-hr $PM_{2.5}$ NAAQS and WHO guidelines

(35) The residential indoor $PM_{2.5}$ were above the 24-hr NAAQS (40 µg.m^{-3}) and WHO (25 µg.m^{-3}) guideline for~57 and 76% of the daily averages.

(36) Based on the seasonal categorisation, the residential indoor $PM_{2.5}$ were above the 24-hr NAAQS and WHO guideline as follows: spring (~74 and 86%) > winter (~61 and 77%) > summer (~50 and 86%).

(37) The individual households showed high intra- and inter-household variability.

(38) KwaZamokuhle showed increased inter-household variability during the spring when compared to summer and winter.

(39) Jouberton also had a high seasonal variability in the number of exceedences experienced from one year to the next.

(40) Agincourt showed less inter-household variability within a single seasonal and less intra-household variability from one season to the next, compared to the settlements within the coal-burning- and urbanised-communities.

(41) Giyani showed less inter-household variability during the spring when compared to summer and winter.

Objective III: *Characterise sources associated with respirable particulate (PM_4) trace elements within the indoor environment of low-income residential settlements in South Africa.*

The objective was addressed through the use of gravimetric filter sampling as described in *Chapter 2, Section 0*. The results and discussion surrounding this objective were presented in *Chapter 4, Section 4.1.2*. The main findings for each sub-objective were as follow:

6.1.2.5. Gravimetric residential indoor PM_4 mass concentrations

(42) The five settlements samples in this study experienced poor indoor air quality associated specifically with the respirable particle fraction. The low-income settlement had a mean (±SD) gravimetric PM_4 loading of 84 (±125) µg.m^{-3}.

(43) Similarly to the continuous PM_4, the coal-burning (126 (±171) µg.m^{-3}) communities experienced mean indoor gravimetric PM_4 loading which was 1.68 and 1.57 times higher than what urbanised- (75 (±138) µg.m^{-3}) and wood-burning (80 (±90) µg.m^{-3}) communities.

(44) There are definite variations in the residential indoor gravimetric PM_4 loadings measured within the individual settlements. KwaZamokuhle had the highest mean (±SD) PM_4 loading with 139 (±160) $\mu g.m^{-3}$. It was a factor of 1.34 higher than its neighbouring coal-burning settlement of KwaDela. It was a factor of 1.85 higher in the urban community of Jouberton. KwaZamokuhle particulate loadings were also 1.75 and 1.59 times higher than the wood-burning communities of Agincourt and Giyani.

(45) Summer PM_4 loadings, for the individual settlements, were in the following order: Giyani > KwaDela > Jouberton > Agincourt > KwaZamokuhle. The particulate loadings in Giyani (113 (±917) $\mu g.m^{-3}$) were higher by factors ranging between 1.08 and 1.68.

(46) Winter PM_4 loadings, for the individual settlements, conformed to the expected as KwaZamokuhle > Agincourt > Jouberton > Giyani. The particulate loadings in KwaZamokuhle (169 (±180) $\mu g.m^{-3}$) were higher by factors ranging between 1.99 and 3.38, thus showing slightly less variation than during the summer.

(47) The spring PM_4 loading in Giyani (136 (±43) $\mu g.m^{-3}$) were higher than those measured during the summer and winter.

(48) Based on the household fuel use classification, the mean PM_4 loading was as follow: ISFB > OSFB > NSFB. The ISFB (111 (±148) $\mu g.m^{-3}$) dwelling experienced particulate loadings 1.49 and 1.42 times higher than NSFB and OSFB households. This trend was observed for all scenarios with the exception of Jouberton during summer (NSFB > ISFB by a factor of 1.40) and in Giyani during spring (OSFB > ISFB by a factor of 1.33).

(49) The individual households had very high intra- and inter-household variability of gravimetric PM_4 loadings, regardless of the community, settlement, season, or fuel use classification.

6.1.2.6. Residential indoor PM_4 trace element mass concentrations

(50) The mean analysed element mass concentration was 33.47 $\mu g.m^{-3}$, accounting for ~40% of the mean gravimetric indoor PM_4 loading in the residential indoor environment of low-income communities in South Africa. The mean element abundance was as follow: i) ***5 to <10%:*** Si and Na; ii) ***1 to <3%:*** Al, Ca, Pb, Zn, Cl, Cu, Fe, Ba, Mg, Sn, K, and S; iii) ***0.1 to <1%:*** Cr, V, Ti, and Mn; and iv) ***<0.1%:*** Br and P.

(51) The mean (±SD) elemental concentrations, in order of abundance was, Si (7.24 (±7.55) $\mu g.m^{-3}$), Na (5.53 (±5.90) $\mu g.m^{-3}$), Al (2.43(±2.56) $\mu g.m^{-3}$), Ca (1.38 (±2.76) $\mu g.m^{-3}$), Pb (1.18 (±2.88) $\mu g.m^{-3}$), Zn (1.80 (±0.95) $\mu g.m^{-3}$), Cl (1.73 (±1.45) $\mu g.m^{-3}$), Cu (1.52 (±1.12) $\mu g.m^{-3}$), Fe (1.40 (±1.97) $\mu g.m^{-3}$), Ba (1.31 (±1.60) $\mu g.m^{-3}$), Mg (1.26 (±1.39) $\mu g.m^{-3}$), Sn (1.24 (±1.13) $\mu g.m^{-3}$), K (1.19 (±1.11) $\mu g.m^{-3}$), S (1.03 (±0.92) $\mu g.m^{-3}$), Cr (0.32 (±0.94) $\mu g.m^{-3}$), V (0.28

(±0.43) µg.m^{-3}), Ti (0.26 (±0.25) µg.m^{-3}), Mn (0.23 (±0.0.38) µg.m^{-3}); Br (0.07 (±0.0.10) µg.m^{-3}) and P (0.05 (±0.05) µg.m^{-3}).

(52) The abundance- and relationship of the elemental mass concentrations are dependent on the contributing sources during the time of sampling.

(53) In the coal-burning communities it was 42.95 µg.m^{-3} (~34%) with mean elemental abundance of i) ***5 to <10%:*** Pb and Na; ii) ***3 to <5%***: Si, Ca, Cu, and Zn; iii) ***1 to <3%:*** Na, Al, S, Cl, K, Fe, and Sn; iv) ***0.1 to <1%:*** Mg, Ti, V, Cr, Mn, and Br; and iv) ***<0.1%:*** P. The elements mass concentrations ratios indicated the following:

- Summer-to-winter ratios showed that Zn and Fe were at unity, while Cl, Ti, V, Cr, Mn, Cu, Ba, and Pb prevailed in summer (41.76 µg.m-3 (~46%)) in addition Na, Mg Si, P, S, K, and Ca were dominant in winter (26.70 µg.m-3 (~36%)).
- Seasonal ISFB-to-NSFB ratios indicated for i) ***summer:*** that S, Br, and Pb were at unity, whereas Cl, Ca, V, Cr, Mn, Fe, Cu, and Pb were dominant in ISFB, with Na, Al, Si, P, K, and Ti were higher in the NSFB; ii) ***winter:*** that P, Ti, Sn, and Pb were at unity, whereas all other elements showed higher concentrations in ISFB.
- KwaDela-to-KwaZamokuhle ratios indicated that Ti, Ba, and Pb were at unity, while Cl, V, Cr, Mn, Fe, Cu, Zn, Sn, and Ba were dominant in KwaDela, in addition, Na, Mg, Al, Si, P, S, K, and Ca were higher KwaZamokuhle.
- There is an amalgamation of sources contributing specifically to Pb.
- The elements which were close to unity in both the ISFB and NSFB dwellings during summer and winter respectively, point toward sources that are dominant within the ambient environment.
- Elements associated with crustal soil sources had higher mass loading in the NSFB household compared to elements of anthropogenic origin.

(54) In the urban community it was 26.70 µg.m^{-3} (~36%) with mean elemental abundance of i) ***5 to <10%:*** Si; ii) ***3 to <5%***: Na; iii) ***1 to <3%:*** Mg, Al, S, Cl, K, Ca, Fe, Cu, Zn, Sn, Ba, and Pb; iv) ***0.1 to <1%:*** Ti, V, Cr, and Mn; and iv) ***<0.1%:*** P and Br. The elements mass concentrations ratios indicated the following:

- Summer-to-winter ratios indicated that Al, P, K, Zn, and Sn were at unity, while Mg, Si, Fe, and Br were prevailing in summer (28.45 µg.m-3 (~38%)) in addition Na, S, Cl, Ca, Ti, V, Cr, Mn, Cu, Ba, and Pb were dominant in winter (24.13 µg.m-3 (~32%)).
- Seasonal ISFB-to-NSFB ratios indicated for i) ***summer:*** that P, Ca, Cu, Zn, and Sn was at unity, whereas all other elements showed higher concentrations in ISFB.; ii) ***winter:*** that Al, Si, P, Ti, Mn, Fe, Cu, Zn, Br, and Sn were at unity, whereas Na, Mg, Ca, and Cr were higher in ISFB, while S, Cl, K, V, Ba, and Pb had higher loadings in the NSFB.

- The ISFB dwellings showed a higher seasonal variability.
- Less variation for crustal soil elements was observed
- The higher K concentrations is associated with some level of biomass burning activities.

(55) In the wood-burning communities it was 35.27 µg.m^{-3} (~44%) with mean elemental abundance of i) ***5 to <10%:*** Na and Si; ii) ***1 to <3%:*** Mg, Al, S, Cl, K, Ca, Fe, Cu, Zn, Sn, Ba, and Pb; iii) ***0.1 to <1%:*** Ti, V, Cr, and Mn; and iv) ***<0.1%:*** P and Br. The elements mass concentrations ratios indicated the following:

- Summer-to-winter ratios indicated that Zn, Br, and Sn were at unity, while all the remaining element showed higher concentrations during winter (46.41 µg.m-3 (~56%)) compared to summer (23.35 µg.m-3 (~30%)).
- The elements that were close to unity (Zn, Br, and Sn) had similar mass concentrations, each accounting between 0.1 and 3% of the measured PM_4. This indicates that there is at least one constant ambient source contributing to these elements during both summer and winter.
- Seasonal ISFB-to-NSFB ratios indicated for i) ***summer:*** that Al, Si, Cl, V, Mn, Cu, Zn, Br, and Ba were at unity, whereas P, K, Ca, Ti, Cr, Fe, and Sn were higher in ISFB, while Na and Mg had higher loadings in the NSFB.; ii) ***winter:*** that Na, Mg, Al, Si, P, S, Cl, Ti, V, Mn, Cu, Zn, and Sn) were at unity, whereas Ca, Cr, Fe, and Ba were higher in ISFB, while Br and Pb had higher loadings in the NSFB.
- Seasonal ISFB-to-OSFB ratios indicated for i) ***summer:*** that Na, Mg, Cl, V, Mn, Cu, Zn, and Sn were at unity, whereas Al, Si, P, S, K, Ca, Ti, Br, and Pb were higher in ISFB, while Cr, Fe, and Ba had higher loadings in the OSFB.; ii) ***winter:*** that Na, Si, P, S, Cl, K, Cu, Zn, and Sn were at unity, whereas Mg, Ca, Ti, V, Cr, Mn, Fe, Ba, and Pb were higher in ISFB, while Br had higher loadings in the OSFB.
- Seasonal NSFB-to-OSFB ratios indicated for i) ***summer:*** that Na, Mg, Cl, V, Mn, Cu, Zn, and Sn were at unity, whereas Na, Mg, Al, Si, P, and Zn were higher in NSFB, while Cr, Fe, and Pb had higher loadings in the OSFB.; ii) ***winter:*** that Na, Al, Si, P, Cl, K, Fe, Zn, Br, Sn, Ba were at unity, whereas Mg, Ti, V, Cr, Mn, Cu, and Pb were higher in NSFB, while S and Ca had higher loadings in the OSFB.
- Small variability between the ISFB, NSFB, and OSF households. The sources are thus expected to contribute similarly within the various households, during summer and winter.
- Agincourt-to-Giyani ratios indicated that Mg, S, K, and Zn were at unity, while Na, Al, Si, Cl, Ca, V, Mn, Cu, Br, and Ba had higher loadings in Agincourt, while P, Ti, Cr, Fe, Sn, and Pb were higher in Giyani.

6.1.2.7. Crustal soil enrichment of residential indoor PM_4 trace element

(56) The mean crustal element enrichment (Al as reference) within the residential indoor environment were as follow: i) ***low (<5):*** Si; ii) ***moderate (>5 -≤10):*** Mg, P, and K; iii) ***high (>10-1000):*** Na, S, Ca, Ti, Mn, and Fe; and iv) ***extreme (>1000):*** Cl, V, Cr, Cu, Zn, Br, Sn, Ba, and Pb. These EFs classify the elements into two groups, namely natural and anthropogenic. The natural (crustal soil) elements included Si, Mg, P, and K. The anthropogenic elements included Na, Ca, S, Ti, Mn, Fe, Cl, V, Cr, Cu, Zn, Br, Sn, Ba, and Pb. It should be noted that multiple sources (natural and anthropogenic) could contribute to the atmospheric loading of specific elements at a single receptor at the same time.

(57) The EF ratios indicated the urban- and wood-burning communities showed similarities in its mean levels of enrichment, whereas the coal-burning communities had experienced much higher EFs:

- The coal-to-urban and coal-to-wood EF ratios showed coal-burning communities EFs were higher than both the urbanised- and wood-burning communities. The coal-to-wood ratios showed larger community variations than the coal-to-urban.
- The urban-to-wood EF ratios indicated that the levels of enrichment for Mg, Si, and P were at unity. Na and K had higher enrichment in the wood-burning community, with the remaining elements showing higher EFs in the urbanised community.

(58) In the coal-burning communities the elements mean EF ratios indicated the following:

- Seasonal ISFB-to-NSFB ratios indicated for i) ***summer:*** that all elements had higher levels of enrichment during summer in ISFB; ii) ***winter:*** that majority of the elements had higher enrichment in the ISFB dwellings, with the exception of Ti and Pb that were increased in ISFB.
- Similar levels of enrichment in the ISFB households during both summer and winter. This points towards similar sources contributing to the mass loadings of these elements in the ISFB. However, the higher level of enrichment experienced in the NSFB households during winter, indicates higher contribution of anthropogenic sources compared to summer.
- KwaDela-to-KwaZamokuhle ratios indicated that all elements had higher levels of enrichment in KwaDela.
- ISFB households in KwaDela are influenced more significantly by anthropogenic sources, during summer, than KwaZamokuhle.
- KwaZamokuhle the ISFB- and OSFB houses show greater variability in its contributing sources than during winter.

(59) In the urbanised communities the elements EF ratios indicated the following:

- Summer-to-winter ratios indicated that P, Cr, and Na were at unity while higher enrichment levels were observed in i) ***summer:*** Ti, Cl, Ca, K, Mg, Mn, V, Ba, and Pb and ii) ***winter:*** Fe, Sn, Zn, Cu, Br, and Si.
- Seasonal ISFB-to-NSFB ratios indicated for i) ***summer:*** that Si was at unity, whereas all other elements showed enrichment in ISFB.; ii) ***winter:*** that P, Sn, Si and Mg were at unity, whereas Ca, K, and Cl were higher in ISFB, and Ba, V, Mn, Fe, Cr, Ti, Br, Pb, Zn, Cu, Na, and S had higher enrichment in the NSFB.

(60) In the wood-burning communities the elements EF ratios indicated the following:

- Spring-to-summer ratios indicated that Si was at unity while higher enrichment levels were observed in i) ***spring:*** Mg and ii) ***winter:*** all remaining elements.
- Spring-to-winter ratios indicated that Si, Ti, and Pb were at unity while higher enrichment levels were observed in i) ***spring:*** V, Cr, Br, Cu, Mn, Zn, Sn, Cl, Ca, Na, Fe, and S and ii) ***winter:*** K, P, and Mg.
- Mg is associated with wood- and biomass burning.
- Summer-to-winter ratios indicated that Si was at unity while higher enrichment levels were observed for all other elements during summer.
- The assumption is that biomass burning is a larger contributor during spring as a result of regional biomass burning events.
- The spring and winter exhibited similar trends, as the majority of elements had higher levels of enrichment within the ISFB households. Elements such as Zn, Sn, and K had increased enrichment in the ISFB houses, indicating road traffic-, waste burning-, and biomass combustion emission might be higher within these households. The inverse is true for the summer, whereby the all elements, excluding Ba and Pb, showed higher enrichment in the OSFB dwellings, which could possibly be linked to higher contributions from road traffic-, waste burning- and residential solid fuel combustion emission.
- The Agincourt-to-Giyani ratios indicate that K was at unity, while higher enrichment levels were observed in i) ***Agincourt:*** Si, Cl, Br, Ca, V, Sn, Zn, Cu, Ba, and Mn and ii) ***Giyani:*** Cr, Fe, Ti, Pb, Mg, Na, P, and S.
- Biomass burning and road traffic emissions are likely the largest contributors to indoor PM_4 within Giyani, whereas Agincourt has a more diverse set of contributing sources.

6.1.2.8. Sources related to residential indoor PM_4 trace elements

(61) The relationship that exists between the trace elements is a good indicator of elements that might have the same or similar origin. In addition, it implies the number of sources that could possibly contribute to the atmospheric concentrations of these elements within the indoor

environment. Five (5) source emission categories were identified based on the mean indoor elemental relationship that exists inside the residences.

- ***Crustal soil:*** Si had strong correlations with Al, Mg, K, P, Na, Ca, and S. Based on the element/Si correlation Al had a single contributing source, whereas Mg and Ca had two, and K, P, Na, and S had at least three. Cu, Zn, Pb, Ba, V, Sn, Br, Mn, Cl, and Cr showed very week negative correlation with Si suggesting that these elements originates from anthropogenic activities. This is supported by the level of enrichment observed for these elements.
- ***Road traffic:*** Zn had strong correlations with Cu, Ba, Pb, V, Mn, Ti, and Cl.
- ***Solid fuel combustion:*** Pb had strong correlations with V, Mn, Cl, SN, and Br.
- ***Waste burning:*** Sn had strong correlations with Zn, Cu, Pb, Ba, Ti, Mn, Cl, and Br.
- ***Biomass burning:*** Na had strong correlations with Mg, K, and Ca. Cl had strong correlations with V, Mn, Ba, Cu, and Zn. K had strong correlations with P.

(62) The correlations support the idea that multiple sources contribute to the individual PM_4 elemental mass concentrations within the indoor environment of low-income residential settlements in South Africa.

6.1.2.9. Qualitative source contribution associated with residential indoor PM_4 trace elements

(63) Five (5) generic source, as described above, were used to categorise the qualitative source contributions. The main sources contributing to PM_4 loadings within the residential indoor environment of low-income included i) crustal soil (35.02%) - Si, Al, K, P, Ca, Mg, and Na; ii) a combination of combustion- and road traffic (33.57%) - V, Ba, Mn, Cu, Cl, Pb, Zn, and Ti; iii) waste burning (7.22%) - Zn, Sn, Pb, Ti, and Cu emissions. The unaccounted-for fraction was 24.19%.

(64) Contributions from coal combustion could be even higher if the carbonaceous species where quantified in the analysis. This is due to the high level of non-combusted carbon associated with inefficient residential burning.

(65) In the coal-burning communities, the contributing sources included crustal soil (38.57%), road traffic emission (31.43%), and solid fuel combustion (8.93%).

- Seasonal variations - i) ***summer:*** crustal soil (46.27%), road traffic (29.94%); and waste burning (31.43%) ii) ***winter:*** solid fuel burning (43.91%), crustal soil (26.31%), road traffic (7.04%), and waste burning (5.58%).
- Settlement variations – i) ***KwaDela***: solid fuel combustion (65.30%), crustal soil (9.07%), and biomass burning (5.11%); ii) ***KwaZamokuhle:*** crustal soil (40.57%), road traffic

(26.24), solid fuel combustion (10.31%), and waste burning (5.09%). The contribution of solid waste burning during summer and winter was 11.03 and 43.91%, respectively.

- These two settlements are similar in many ways (geographic location, proximity to roads, climate, etc.), the contribution of specific sources are highly impacted by the activities which occur locally.
- Household variations – in KwaZamokuhle within the ISFB and NSFB i) ***summer:*** crustal soil (54.98 and 32.27%), road traffic (10.92 and 8.51%), solid fuel combustion (7.00 and 12.40%), and waste burning (6.21 and 13.41%); ii) ***winter:*** crustal soil (28.88 and 35.02%), solid fuel combustion (43.25 and 17.76%), and waste burning (6.6.34 and 9.59%), road traffic (n/a and 15.84%) emission.
- Waste burning emission were close to unity (ambient source), while solid fuel combustion emissions were higher during the winter. Crustal soil- and road traffic emissions were more prevalent in the summer.

(66) In the urbanised communities the contributing sources included crustal soil (42.10%), solid fuel combustion (22.52%), and road traffic (9.43%).

- Seasonal variation - i) ***summer:*** road traffic (49.42%), crustal soil (23.79%); and waste burning (6.96%) ii) ***winter:*** crustal soil (37.48%), road traffic (14.50%), solid fuel combustion (10.58%), waste burning (5.64%), and biomass burning (5.10%).
- Residential solid fuel burning and biomass burning sources were unexpected.
- Household variations – in Jouberton within the ISFB and NSFB i) ***summer:*** crustal soil (24.52 and 23.90%), road traffic (45.04 and 49.87%), and waste burning (6.65 and 6.90%), and biomass burning (5.62% and n/a); ii) ***winter:*** biomass burning (29.41 and 5.16%), crustal soil (20.35 and 39.92%), road traffic (10.43 and 14.73%), solid fuel combustion (6.77 and 9.81%), and waste burning (7.02 and 5.69%) emissions.
- Combustions of solid fuels, such as coal and wood, were more prevalent during the winter within the ISFB-and NSFB dwellings of the urban low-income settlement.
- Waste burning emissions, mainly originate in the ambient environment and appear to be a constant source across all seasons.

(67) In the wood-burning communities, the contributing sources included crustal soil (37.70%), road traffic emission (28.08%), and biomass burning (6.48%).

- Seasonal variation - i) ***summer:*** crustal soil (35.00%), road traffic (21.76%); and biomass burning (7.59%) ii) ***winter:*** crustal soil (34.39%), road traffic (31.93%), biomass burning (7.94%), and waste burning (5.58%).
- Sources are constants at the community level, lending support to the assumption that most of the sources have an ambient origin in the wood burning communities.

- Settlement variations – i) ***Agincourt***: crustal soil (39.18%), road traffic (28.29%), biomass burning (6.43%), and waste burning (5.83%); ii) ***Giyani:*** crustal soil (36.89%), road traffic (25.99%), and biomass burning (12.89%).
- Communities within the Lowveld-region are reliant of wood-burning as a primary source of energy.
- Biomass burning is not identified as the dominant source, but does have a discernable impact on indoor PM_4.
- Household variations – in Agincourt within the ISFB, NSFB, and OSFB i) ***summer:*** biomass burning (9.68, 6.51, and 8.20%), crustal soil (34.20, 45.01, and 39.33%), road traffic (18.21, 16.70, and 12.95%), and solid fuel combustion (7.99, 7.03, and 5.87%), and waste burning (n/a, n/a, and 5.20%) emission; ***winter:*** biomass burning (7.49, 10.93, and 7.88%), crustal soil (35.50, 23.56, and 37.17%), road traffic (34.73, 42.69, and 31.57%), and waste burning (6.06, 6.08, and 5.62%) emissions.
- Higher abundance of crustal soil emissions is almost certainly a result of poor vegetative cover and low rainfall during winter with the Giyani region.

(68) The abundance, enrichment, and relationship of the elemental mass concentrations are dependent on the sources present during the time of sampling. All of which are impacted by the activities practices by residents within and around the settlements as well as the local meteorological condition.

6.1.3. Meteorology of the study area

Objective IV: *Investigate the influence of regional synoptics on local meteorology and its associated impact on particulate pollution in the indoor environment of low-income residential settlements in South Africa.*

The objective was addressed through the use of synoptic and meteorological data as described in *Chapter 2, Section 2.3.2.5.2* in conjunction with the indoor continuous and gravimetric PM_4. The results and discussion surrounding this objective were presented in *Chapter 5*. The main findings for each sub-objective are as follow:

6.1.3.1. Observed regional synoptics and local meteorological conditions

(69) The most dominant synoptic circulation conditions, in order of abundance, included i) continental anticyclones (43.32%); ii) easterly waves (27.59%), iii) ridging anticyclones (13.79%), iv) cut-off lows (9.48%) and v) westerly waves (3.34%). The observed synoptic circulations frequency of occurrence are thus similar to the climatic historical data.

(70) Local wind field influence the dispersion and transportation of pollutants emitted close to the surface. The wind roses depicted high seasonal and day-night variability in the surface flow observed in the five sampled settlements. High wind speeds are expected to increase the mobilisation particulate aerosols, increasing levels of transportation and infiltration into the indoor environment of residential homes.

(71) Temperature and relative humidity impacts not only on the behaviour particulate aerosols but also on the behaviour of people. It influences people to partake in activities such as residential combustion due to cold temperatures or manual ventilating the dwelling due to increased temperatures. All actions taking place in and around the house will impact on the particulate loading inside the home. The daily averages showed mean (±SD) that ambient temperatures:

- where in the following order: spring (18.4 (±7.1)) > summer (18.8 (±5.4)) > winter (12.5 (±6.9)).
- have a specific diurnal pattern with the highest temperatures occurring between 10h00 and 14h00, while the lowest temperatures are recorded between 04h00 and 07h00.

(72) The relative humidity daily averages indicated mean (±SD) measurements in the following order: summer (68.8 (±20.6)) > spring (60.0 (±24.0)) > winter (49.9 (±25.7)). The diurnal pattern was the inverse of that observed for temperature.

(73) The assumption is made that the individual campaigns sampled during the study, both in the Highveld and Lowveld regions, are representative of the typical meteorological conditions experienced in South Africa during spring, summer and winter.

6.1.3.2. Impact on residential indoor PM_4 mass concentrations;

(74) Synoptic patterns associate with different levels of indoor PM4 within the low-income residential settlements in South Africa.

(75) The impact differs between type of coal-burning-, urban-, and wood burning communities.

(76) Synoptic patterns associated with cold spells had the highest indoor PM_4 in all settlements, however, is was more pronounced in the coal-burning communities.

(77) Large variability exists within each of the synoptic circulation regimes and between communities.

Indoor particulate pollution was investigated and characterised in five settlements located across two main geographic regions. The finding from the investigation indicated a high variability across these settlement, which limits the ability to extrapolate the data to other similarly categorised settlements. It is safe to assume that indoor particulate pollution is a relevant problem within low-income residential communities which requires further in-depth investigation in future.

6.2. Contribution to the current body of knowledge

(1) The use of photometric instruments to quantify the particulate loading within a diverse set of indoor environments (coal-burning, urban, and wood-burning) has been assessed and calibrated for the first time in South Africa.

(2) The study is the first comprehensive assessment of indoor particulate matter air pollution across different geographical regions of South Africa.

(3) Comparison of indoor PM_4 within different types of households, across various low-income communities in South Africa has been quantified.

(4) Elemental characterisation of PM_4 within the indoor environment of residential low-income communities has been undertaken for the first time in in South Africa spanning different spatial locations and seasonal variability.

(5) A qualitative source characterisation of PM_4 within the indoor environment of residential low-income communities in South Africa has been achieved in three different community types. This study lays the basis for comprehensive intervention and management strategies aligned with the Governments stated focus on low-income settlements for the foreseeable future.

(6) The role that atmospheric conditions, including temperature, humidity and circulation has on possible indoor PM loadings has been thoroughly assessed for the first time in South Africa.

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This chapter summarised the main findings as they pertain to each research objective outlined in *Chapter 1, Section 1.4*,

REFERENCES

Adesina, J.A., Piketh, S.J., Qhekwana, M., Burger, R., Language, B., & Mkhatshwa, G. 2020. Contrasting indoor and ambient particulate matter concentrations and thermal comfort in coal and non-coal burning households at South Africa Highveld. *Science of The Total Environment*. *Elsevier BV*. 699:134403.

Adgate, J.L., Willis, R.D., Buckley, T.J., Chow, J.C., Watson, J.G., Rhoads, G.G., & Lioy, P.J. 1998. Chemical Mass Balance Source Apportionment of Lead in House Dust. *Environment Science Technology*. 32:108–114.

Akimoto, H. 2003. Global Air Quality and Pollution. *Science*. 302:1716–1719.

Alastuey, A., Querol, X., Plana, F., Viana, M., Ruiz, C.R., & Sánchez De La Campa, A. 2006. Identification and Chemical Characterization of Industrial Particulate Matter Sources in Southwest Spain. *Journal of the Air & Waste Management Association*. 56(7):993–1006.

Albers, P.N., Wright, C.Y., Voyi, K.V. V, & Mathee, A. 2015. Household fuel use and child respiratory ill health in two towns in Mpumalanga, South Africa. *South African Medical Journal*. 105(7):573–577.

Ali, M.Y., Hanafiah, M.M., Khan, M.F., & Latif, M.T. 2017. Quantitative source apportionment and human toxicity of indoor trace metals at university buildings. *Building and Environment*. *Pergamon*. 121:238–246.

Alleman, L.Y., Lamaison, L., Perdrix, E., Robache, A., & Galloo, J.-C. 2010. PM10 metal concentrations and source identification using positive matrix factorization and wind sectoring in a French industrial zone. *Atmospheric Research*. 96(4):612–625.

Amato, F., Pandolfi, M., Moreno, T., Furger, M., Pey, J., Alastuey, A., Bukowiecki, N., Prevot, A.S.H., Baltensperger, U., & Querol, X. 2011. Sources and variability of inhalable road dust particles in three European cities. *Atmospheric Environment*. 45(37):6777–6787.

Amato, F., Rivas, I., Viana, M., Moreno, T., Bouso, L., Reche, C., Àlvarez-Pedrerol, M., Alastuey, A., Sunyer, J., & Querol, X. 2014. Sources of indoor and outdoor PM2.5 concentrations in primary schools. *Science of The Total Environment*. *Elsevier*. 490:757–765.

Amegah, A.K. & Agyei-Mensah, S. 2017. Urban air pollution in Sub-Saharan Africa: Time for action. *Environmental Pollution*. *Elsevier*. 220:738–743.

Amegah, A.K., Quansah, R., & Jaakkola, J.J.K. 2014. Household Air Pollution from Solid Fuel Use and Risk of Adverse Pregnancy Outcomes: A Systematic Review and Meta-Analysis of the Empirical Evidence.

PLoS ONE. *Public Library of Science*. 9(12).

Anderson, M.J., Daly, E.P., Miller, S.L., & Milford, J.B. 2002. Source apportionment of exposures to volatile organic compounds: II. Application of receptor models to TEAM study data. *Atmospheric Environment*. *Pergamon*. 36(22):3643–3658.

Argyropoulos, G., Grigoratos, T., Voutsinas, M., & Samara, C. 2013. Concentrations and source apportionment of PM10 and associated elemental and ionic species in a lignite-burning power generation area of southern Greece. *Environmental Science and Pollution Research*. *Springer Berlin Heidelberg*. 20(10):7214–7230.

Ayo-Yusuf, O.A., Olufajo, O., & Agaku, I.T. 2014. Exposure to secondhand smoke and voluntary adoption of smoke-free home and car rules among non-smoking South African adults. *BMC Public Health*. 14:580.

Balakrishnan, K., Ramaswamy, P., Sambandam, S., Thangavel, G., Ghosh, S., Johnson, P., Mukhopadhyay, K., Venugopal, V., & Thanasekaraan, V. 2011. Global Health Action Air pollution from household solid fuel combustion in India: an overview of exposure and health related information to inform health research priorities. *Global Health Action*. 4:5638.

Balmer, M. 2007. Household coal use in an urban township in South Africa. *Journal of Energy in Southern Africa*. 18(3):27–32.

Bano, S., Pervez, S., Chow, J.C., Matawle, J.L., Watson, J.G., Sahu, R.K., Srivastava, A., Tiwari, S., Pervez, Y.F., & Deb, M.K. 2018. Coarse particle (PM10–2.5) source profiles for emissions from domestic cooking and industrial process in Central India. *Science of The Total Environment*. *Elsevier*. 627:1137–1145.

Bari, A., Kindzierski, W.B., Wheeler, A.J., Héroux, M.-È., & Wallace, L.A. 2015. Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada. *Building and Environment*. *Pergamon*. 90:114–124.

Barnes, B., Mathee, A., & Moiloa, K. 2005. Assessing child time – activity patterns in relation to indoor cooking fires in developing countries: A methodological comparison. *International Journal of Hygiene and Environmental Health*. *Urban & Fischer*. 208(3):219–225.

Barnes, B., Mathee, A., Thomas, E., & Bruce, N.G. 2009. Household energy, indoor air pollution and child respiratory health in South Africa. *Journal of Energy in Southern Africa*. 20(1):4–13.

Barnes, B.R. 2014. Behavioural Change, Indoor Air Pollution and Child Respiratory Health in Developing Countries: A Review. *Int. J. Environ. Res. Public Health*. 11:4607–4618.

Barnes, B.R., Mathee, A., Bruce, N.G., & Thomas, E. 2006. Protecting children from indoor air pollution exposure through outdoor cooking in rural South Africa. *Boiling Point*. 52:11–13.

Barnes, B.R., Mathee, A., Krieger, L., Shafritz, L., Favin, M., & Sherburne, L. 2004. Testing selected behaviors to reduce indoor air pollution exposure in young children. *Health Education Research*. *Oxford University Press*. 19(5):543–550.

Barnes, B.R., Mathee, A., & Thomas, E. 2011. The impact of health behaviour change intervention on indoor air pollution indicators in the rural North West Province, South Africa. *Journal of Energy in Southern Africa*. 22(3):35–44.

Barraza, F., Jorquera, H., Valdivia, G., & Montoya, L.D. 2014. Indoor PM2.5 in Santiago, Chile, spring 2012: Source apportionment and outdoor contributions. *Atmospheric Environment*. *Pergamon*. 94:692–700.

Bates, M.N., Chandyo, R.K., Valentiner-Branth, P., Pokhrel, A.K., Mathisen, M., Basnet, S., Shrestha, P.S., Strand, T.A., & Smith, K.R. 2013. Acute lower respiratory infection in childhood and household fuel use in Bhaktapur, Nepal. *Environmental Health Perspectives*. 121(5):637–642.

Belis, C.A., Karagulian, F., Larsen, B.R., & Hopke, P.K. 2013. Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe Particulate matter Source apportionment Receptor models Europe Exceedances Carbonaceous fraction Particulate organic carbon. *Atmospheric Environment*. 69:94–108.

Bernstein, J.A., Alexis, N., Bacchus, H., Bernstein, I.L., Fritz, P., Horner, E., Li, N., Mason, S., Nel, A., Oullette, J., Reijula, K., Reponen, T., Seltzer, J., Smith, A., & Tarlo, S.M. 2008. The health effects of nonindustrial indoor air pollution. *Journal of Allergy and Clinical Immunology*. *Mosby*. 121(3):585–591.

Bi, X., Dai, Q., Wu, J., Zhang, Q., Zhang, W., Luo, R., Cheng, Y., Zhang, J., Wang, L., Yu, Z., Zhang, Y., Tian, Y., & Feng, Y. 2019. Characteristics of the main primary source profiles of particulate matter across China from 1987 to 2017. *Atmos. Chem. Phys*. 19:3223–3243.

Block, C. & Dams, R. 1975. Lead contents of coal, coal ash and fly ash. *Water, Air, and Soil Pollution*. *Kluwer Academic Publishers*. 5(2):207–211.

Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N.G., Mehta, S., Prüss-Ustün, A., Lahiff, M., Rehfuess, E.A., Mishra, V., & Smith, K.R. 2013. Solid fuel use for household cooking: Country and regional estimates for 1980-2010. *Environmental Health Perspectives*. 121(7):784–790.

Boy, E., Bruce, N., & Delgado, H. 2002. Birth Weight and Exposure to Kitchen Wood Smoke During

Pregnancy in Rural Guatemala. , Environmental Health Perspectives.

Braniš, M. & Hovorka, J. 2005. Performance of a photometer DustTrak in various indoor and outdoor environments. , in: Abstracts of the 2005 Evaluation and Assessment Conference (EAC 2005). . p. 535.

Bruce, N., Dherani, M., Liu, R., Hosgood, H.D., Sapkota, A., Smith, K.R., Straif, K., Lan, Q., & Pope, D. 2015. Does household use of biomass fuel cause lung cancer? A systematic review and evaluation of the evidence for the GBD 2010 study. *Thorax*. *BMJ Publishing Group Ltd*. 70(5):433–41.

Brunekreef, B. & Holgate, S.T. 2002. Air pollution and health. *The Lancet*. *Elsevier*. 360(19 Oct):1233–1242.

Buczyńska, A.J., Krata, A., Van Grieken, R., Brown, A., Polezer, G., De Wael, K., & Potgieter-Vermaak, S. 2014. Composition of PM2.5 and PM1 on high and low pollution event days and its relation to indoor air quality in a home for the elderly. *Science of The Total Environment*. *Elsevier*. 490:134–143.

Cadle, R.D. & Wohlers, H.C. 1952. Smog Lore. *Air Repair*. 1(4):30–35.

Campbell Scientific Inc. 2017. LoggerNet, Version 4.x.

Cesari, D., Contini, D., Genga, A., Siciliano, M., Elefante, C., Baglivi, F., & Daniele, L. 2012. Analysis of raw soils and their re-suspended PM10 fractions: Characterisation of source profiles and enrichment factors. *Applied Geochemistry*. *Pergamon*. 27(6):1238–1246.

Chafe, Z., Brauer, M., Klimont, Z., Van Dingenen, R., Mehta, S., Rao, S., Riahi, K., Dentener, F., & Smith, K. 2014. Household cooking with solid fuels contributes to ambient PM2. *Environ Health Perspect*. 122(12):1314–20.

Chakraborty, D., Mondal, N.K., & Datta, J.K. 2014. Indoor pollution from solid biomass fuel and rural health damage: A micro-environmental study in rural area of Burdwan, West Bengal. *International Journal of Sustainable Built Environment*. *Elsevier*. 3(2):262–271.

Chen, P., Wang, T., Dong, M., Kasoar, M., Han, Y., Xie, M., Li, S., Zhuang, B., Li, M., & Huang, T. 2017. Characterization of major natural and anthropogenic source profiles for size-fractionated PM in Yangtze River Delta. *Science of The Total Environment*. *Elsevier*. 598:135–145.

Chen, X.-C., Jahn, H.J., Engling, G., Ward, T.J., Kraemer, A., Ho, K.-F., Yim, S.H.L., & Chan, C.-Y. 2017. Chemical characterization and sources of personal exposure to fine particulate matter (PM2.5) in the megacity of Guangzhou, China. *Environmental Pollution*. *Elsevier*. 231:871–881.

Chen, Z.H., Cheng, S.Y., Li, J.B., Guo, X.R., Wang, W.H., & Chen, D.S. 2008. Relationship between

atmospheric pollution processes and synoptic pressure patterns in northern China. *Atmospheric Environment. Pergamon*. 42(24):6078–6087.

Chow, J.C., Engelbrecht, J.P., Freeman, N.C.G., Hisham Hashim, J., Jantunen, M., Michaud, J.P., De Tejada, S.S., Watson, J.G., Wei, F., Wilson, W.E., Yasuno, M., & Zhu, T. 2002. Chapter one: Exposure measurements. *Chemosphere*. 49(9):873–901.

Chow, J.C., Watson, J.G., Kuhns, H., Etyemezian, V., Lowenthal, D.H., Crow, D., Kohl, S.D., Engelbrecht, J.P., & Green, M.C. 2004. Source profiles for industrial, mobile, and area sources in the Big Bend Regional Aerosol Visibility and Observational study. *Chemosphere*. 54:185–208.

Chung, A., Chang, D.P.Y., Kleeman, M.J., Perry, K.D., Cahill, T.A., Dutcher, D., McDougall, E.M., & Stroud, K. 2001. Comparison of real-time instruments used to monitor airborne particulate matter. *Journal of the Air and Waste Management Association*. 51(1):109–120.

Colombi, C., Gianelle, V.L., Belis, C.A., & Larsen, B.R. 2010. Determination of local source profile for soil dust, brake dust and biomass burning sources. *Chemical Engineering Transactions*. 22:233–238.

Cooper, J.A. & Watson, J.G. 1980. Receptor Oriented Methods of Air Particulate Source Apportionment. *Journal of the Air Pollution Control Association*. 30(10):1116–1125.

Core, J.E., Cooper, J.A., Hanrahan, P.L., & Cox, W.M. 1982. Particulate Dispersion Model Evaluation: A New Approach Using Receptor Models. *Journal of the Air Pollution Control Association*. 32(11):1142–1147.

Crutzen, P.J. 2002. Geology of mankind. *Nature*. *Nature Publishing Group*. 415(6867):23–23.

Crutzen, P.J. 2006. The "Anthropocene." , in: Earth System Science in the Anthropocene. Springer-Verlag: Berlin/Heidelberg. . Springer-Verlag: Berlin/Heidelberg, pp. 13–18.

Dales, R., Liu, L., Wheeler, A.J., & Gilbert, N.L. 2008. Public health: Quality of indoor residential air and health. *CMAJ*. 179(2):147–152.

Davis, D.L. & Bell, M.L. 2002. A Look Back at the London Smog of 1952 and the Half Century Since. *Environmental Health Perspectives*. 110(12):734–735.

De Miguel, E., Llamas, J.F., Chacón, E., Berg, T., Larssen, S., Røyset, O., & Vadset, M. 1997. Origin and patterns of distribution of trace elements in street dust: Unleaded petrol and urban lead. *Atmospheric Environment*. 31(17):2733–2740.

Department of Health. 2017. Guidline for Monitoring Domestic Indoor Air Quality (Draft).

Department of Minerals and Energy. 1998. White Paper on the Energy Policy of the Republic of South Africa.

Dherani, M., Pope, D., Mascarenhas, M., Smith, K.R., Weber, M., & Bruce, N. 2008. Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. *Bulletin of the World Health Organization*. *World Health Organization*. 86(5):390–398.

Dhimal, M., Baral, K., Shrestha, N., Dhakal, P., & Maskey, M.K. 2010. Environmental Burden of Acute Respiratory Infection and Pneumonia due to Indoor Smoke. *Journal of Nepal Health Research Council*. 8(16 Apr):1–4.

du Preez, K., Mandalakas, A.M., Kirchner, H.L., Grewal, H.M.S., Schaaf, H.S., van Wyk, S.S., & Hesseling, A.C. 2011. Environmental tobacco smoke exposure increases Mycobacterium tuberculosis infection risk in children. *The International Journal of Tuberculosis and Lung Disease*. 15(11):1490–1497.

Dunning, H., Allison, A.E., Ae, W., Ae, S.A., Crooks, V., Dunning, H., Williams, A., Abonyi, S., & Crooks, V. 2008. A Mixed Method Approach to Quality of Life Research: A Case Study Approach. *Soc Indic Res*. 85:145–158.

Ehrlich, R.I., White, N., Norman, R., Laubscher, R., Steyn, K., Lombard, C., & Bradshaw, D. 2004. Predictors of chronic bronchitis in South African adults. *International Journal of Tuberculosis and Lung Disease*. *International Union Against Tuberculosis and Lung Disease*. 8(3):369–376.

El Haddad, I., Marchand, N., Dron, J., Temime-Roussel, B., Quivet, E., Wortham, H., Jaffrezo, J.L., Baduel, C., Voisin, D., Besombes, J.L., & Gille, G. 2009. Comprehensive primary particulate organic characterization of vehicular exhaust emissions in France. *Atmospheric Environment*. *Pergamon*. 43(39):6190–6198.

Elf, J.L., Eke, O., Rakgokong, M., Variava, E., Baliram, Y., Motlhaoleng, K., Lebina, L., Shapiro, A.E., Breysse, P.N., Golub, J.E., & Martinson, N. 2017. Indoor air pollution from secondhand tobacco smoke, solid fuels, and kerosene in homes with active tuberculosis disease in South Africa. *BMC Research Notes*. 10:591.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G., & Egami, R.T. 2001. {PM2.5} and {PM10} Concentrations from the Qalabotjha {Low-Smoke} Fuels {Macro-Scale} Experiment in South Africa. *Environ. Monit. Assess.* 69:1–15.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G., & Egami, R.T. 2002. The comparison of

source contributions from residential coal and low-smoke fuels, using CMB modeling, in South Africa. *Environmental Science and Policy*. 5(2):157–167.

Ezeh, G.C., Obioh, I.B., & Asubiojo, O.I. 2017. Trace Metals and Source Identification of Air-Borne Particulate Matter Pollution in A Nigerian Megacity. *Journal of Environmental & Analytical Toxicology*. *OMICS Publishing Group*. 07(03).

Ezzati, M. & Kammen, D.M. 2001. Indoor air pollution from biomass combustion and acute respiratory infections in Kenya: an exposure-response study. *The Lancet. Elsevier*. 358(25 Aug):619–624.

Ezzati, M. & Kammen, D.M. 2002. The Health Impacts of Exposure to Indoor Air Pollution for Solid Fuels in Developing Countries: Knowledge, Gaps, and Data Needs. *Environmental Health Perspectives*. 110(11):1057–1068.

Fatmi, Z., Coggon, D., Kazi, A., Naeem, I., Kadir, M.M., & Sathiakumar, N. 2014. Solid fuel use is a major risk factor for acute coronary syndromes among rural women: a matched case control study. *Public Health. W.B. Saunders*. 128(1):77–82.

Fernández, L.C., Alvarez, R.F., González-Barcala, F.J., & Portal, J.A.R. 2013. Indoor Air Contaminants and their Impact on Respiratory Pathologies. *Archivos de Bronconeumologia*. *SEPAR*. 49(1):22–27.

Fernández, T.A. & Casan, P.C. 2012. Deposition of Inhaled Particles in the Lungs. *Archivos de Bronconeumología (English Edition)*. *Elsevier Doyma*. 48(7):240–246.

Fine, P.M., Cass, G.R., & Simoneit, B.R.T. 2001. Chemical Characterization of Fine Particle Emissions from Fireplace Combustion of Woods Grown in the Northeastern United States. *Environ. Sci. Technol.* 35:2665–2675.

Fine, P.M., Cass, G.R., & Simoneit, B.R.T. 2004. Chemical Characterization of Fine Particle Emissions from the Wood Stove Combustion of Prevalent United States Tree Species. *Environmental Engineering Science*. 21(6):705–721.

Firket, J. 1936. Fog along the Meuse Valley. *Transactions of the Faraday Society*. 32:1192–1196.

Friedlander, S.K. & Keck, M. 1973. Chemical Element Balances and Identification of Air Pollution Sources. *Environmental Science & Technology*. 7(3):235–240.

Gadkari, N. & Pervez, S. 2008. Source apportionment of personal exposure of fine particulates among school communities in India. *Environmental Monitoring Assessment*. 142:227–241.

Gadkari, N.M. & Pervez, S. 2007. Source investigation of personal particulates in relation to identify

major routes of exposure among urban residentials. *Atmospheric Environment*. *Pergamon*. 41(36):7951–7963.

Galeone, C., Pelucchi, C., La Vecchia, C., Negri, E., Bosetti, C., & Hu, J. 2008. Indoor air pollution from solid fuel use, chronic lung diseases and lung cancer in Harbin, Northeast China. *European Journal of Cancer Prevention*. 17(5):473–478.

Gaspar, F.W., Chevrier, J., Bornman, R., Crause, M., Obida, M., Barr, D.B., Bradman, A., Bouwman, H., & Eskenazi, B. 2015. Undisturbed dust as a metric of long-term indoor insecticide exposure: Residential DDT contamination from indoor residual spraying and its association with serum levels in the VHEMBE cohort. *Environment International*. *Pergamon*. 85:163–167.

Gemenetzis, P., Moussas, P., Arditsoglou, A., & Samara, C. 2006. Mass concentration and elemental composition of indoor PM2.5 and PM10 in University rooms in Thessaloniki, northern Greece. *Atmospheric Environment*. *Pergamon*. 40(17):3195–3206.

Gholampour, A., Nabizadeh, R., Hassanvand, M.S., Taghipour, H., Rafiee, M., Alizadeh, Z., Faridi, S., & Mahvi, A.H. 2016. Characterization and source identification of trace elements in airborne particulates at urban and suburban atmospheres of Tabriz, Iran. *Environmental Science and Pollution Research*. 23(2):1703–1713.

Gillings, M.R. & Hagan-Lawson, E.L. 2014. The cost of living in the Anthropocene. *Earth Perspectives*. *Springer Berlin Heidelberg*. 1:2.

Glazewski, J. 2000. Environmental Law in South Africa. Butterworths Publishers (Pty) Ltd: Durban.

Gokhale, S., Kohajda, T., & Schlink, U. 2008. Source apportionment of human personal exposure to volatile organic compounds in homes, offices and outdoors by chemical mass balance and genetic algorithm receptor models. *Science of The Total Environment*. *Elsevier*. 407(1):122–138.

Gordon, G.E. 1988. Receptor models Development and testing of such models has moved from the research domain into application to practical problems. *Environmental Science Technology*. 22(10):1132–1142.

Guo, H. 2011. Source apportionment of volatile organic compounds in Hong Kong homes. *Building and Environment*. *Pergamon*. 46(11):2280–2286.

Guo, Y., Gao, X., Zhu, T., Luo, L., & Zheng, Y. 2017. Chemical profiles of PM emitted from the iron and steel industry in northern China. *Atmospheric Environment*. 150(150):187–197.

Habre, R., Coull, B., Moshier, E., Godbold, J., Grunin, A., Nath, A., Castro, W., Schachter, N., Rohr, A.,

Kattan, M., Spengler, J., & Koutrakis, P. 2014. Sources of indoor air pollution in New York City residences of asthmatic children. *Journal of Exposure Science and Environmental Epidemiology*. 24:269–278.

Hasheminassab, S., Daher, N., Shafer, M.M., Schauer, J.J., Delfino, R.J., & Sioutas, C. 2014. Chemical characterization and source apportionment of indoor and outdoor fine particulate matter (PM2.5) in retirement communities of the Los Angeles Basin. *Science of The Total Environment*. *Elsevier*. 490:528–537.

Heal, M.R., Beverland, I.J., McCabe, M., Hepburn, W., & Agius, R.M. 2000. Intercomparison of five PM10 monitoring devices and the implications for exposure measurement in epidemiological research. *Journal of Environmental Monitoring*. 2(5):455–461.

Henry, R.C., Lewis, C.W., Hopke, P.K., & Williamson, H.J. 1984. Review of receptor model fundamentals. *Atmospheric Environment (1967)*. *Elsevier*. 18(8):1507–1515.

Hersey, S.P., Garland, R.M., Crosbie, E., Shingler, T., Sorooshian, A., Piketh, S., & Burger, R. 2015. An overview of regional and local characteristics of aerosols in South Africa using satellite, ground, and modeling data. *Atmospheric Chemistry and Physics*. *NIH Public Access*. 15:4259.

Hiemstra-van der Horst, G. & Hovorka, A.J. 2008. Reassessing the "energy ladder": Household energy use in Maun, Botswana. *Energy Policy*. 36(9):3333–3344.

Ho, S.S.H., Huang, Y., Lee, S.C., & Cao, J. 2017. Challenges on field monitoring of indoor air quality in China. *Indoor and Built Environment*. 26(4):576–584.

Hopke, P.K. 1991. Receptor modeling for air quality management. Elsevier.

Hopke, P.K. 2003. Recent developments in receptor modeling. *Journal of Chemometrics*. *John Wiley & Sons, Ltd*. 17(5):255–265.

Hopke, P.K. 2016. Review of receptor modeling methods for source apportionment. *Journal of the Air & Waste Management Association*. 66(3):237–259.

Hopke, P.K. & Cohen, D.D. 2011. Application of receptor modeling methods. *Atmospheric Pollution Research*. 2:122–125.

Hopke, P.K., Ramadan, Z., Paatero, P., Norris, G.A., Landis, M.S., Williams, R.W., & Lewis, C.W. 2003. Receptor modeling of ambient and personal exposure samples: 1998 Baltimore Particulate Matter Epidemiology-Exposure Study. *Atmospheric Environment*. *Pergamon*. 37(23):3289–3302.

Huang, W., Baumgartner, J., Zhang, Y., Wang, Y., & Schauer, J.J. 2015. Source apportionment of air

pollution exposures of rural Chinese women cooking with biomass fuels. *Atmospheric Environment*. *Pergamon*. 104:79–87.

Jafta, N., Barregard, L., Jeena, P.M., & Naidoo, R.N. 2017. Indoor air quality of low and middle income urban households in Durban, South Africa. *Environmental Research*. *Academic Press*. 156:47–56.

Jafta, N., Batterman, S.A., Gqaleni, N., Naidoo, R.N., & Robins, T.G. 2012. Characterisation of allergens and airborne fungi in low and middle-income homes of primary school children in Durban, South Africa HHS Public Access. *Am J Ind Med*. 55(12):1110–1121.

Jafta, N., Jeena, P.M., Barregard, L., & Naidoo, R.N. 2015. Childhood tuberculosis and exposure to indoor air pollution: a systematic review and meta-analysis. *The International Journal of Tuberculosis and Lung Disease*. 19(5):596–602.

Jain, S., Sharma, S.K., Mandal, T.K., & Saxena, M. 2018. Source apportionment of PM10in Delhi, India using PCA/APCS, UNMIX and PMF. *Particuology*. *Chinese Society of Particuology*. 37:107–118.

Javitz, H.S., Watson, J.G., Guertin, J.P., & Mueller, P.K. 1988. Results of a Receptor Modeling Feasibility Study. *Journal of the Air Pollution Control Association*. 38(5):661–667.

Jiang, R.T., Acevedo-Bolton, V., Cheng, K.C., Klepeis, N.E., Ott, W.R., & Hildemann, L.M. 2011. Determination of response of real-time SidePak AM510 monitor to secondhand smoke, other common indoor aerosols, and outdoor aerosol. *Journal of Environmental Monitoring*. 13(6):1695–1702.

Johnson, R.B. & Onwuegbuzie, A.J. 2004. Mixed Methods Research: A research paradigm whose time has come. *Educational Researcher*. 33(7):14–26.

Johnson, R.B., Onwuegbuzie, A.J., & Turner, L.A. 2007. Toward a Definition of Mixed Methods Research. *Journal of Mixed Methods Research*. 1(2):112–133.

Joss, M.K., Eeftens, M., Gintowt, E., Kappeler, R., & Künzli, N. 2017. Time to harmonize national ambient air quality standards. *International Journal of Public Health*. *Springer International Publishing*. 62(4):453–462.

Kalaiarasan, G., Balakrishnan, R.M., Sethunath, N.A., & Manoharan, S. 2017. Source Apportionment of PM 2.5 Particles: Influence of Outdoor Particles on Indoor Environment of Schools Using Chemical Mass Balance. *Aerosol and Air Quality Research*. 17:616–625.

Kan, X., Chiang, C.-Y., Enarson, D.A., Chen, W., Yang, J., & Chen, G. 2011. Indoor solid fuel use and tuberculosis in China: a matched case-control study. *BMC Public Health*. *BioMed Central*. 11(1):498.

Kara, M., Dumanoğlu, Y., Altıok, H., Elbir, T., Odabası, M., & Bayram, A. 2014. Spatial distribution and source identification of trace elements in topsoil from heavily industrialized region, Aliaga, Turkey. *Environ Monit Assess*. 186:6017–6038.

Kim, D., Sass-Kortsak, A., Purdham, J.T., Dales, R.E., & Brook, J.R. 2005. Sources of Personal Exposure to Fine Particles in Toronto, Ontario, Canada. *Journal of the Air & Waste Management Association*. 55(8):1134–1146.

Kim, K.-H., Jahan, S.A., & Kabir, E. 2011. A review of diseases associated with household air pollution due to the use of biomass fuels. *Journal of Hazardous Materials*. *Elsevier*. 192(2):425–431.

Kingham, S., Durand, M., Aberkane, T., Harrison, J., Gaines Wilson, J., & Epton, M. 2006. Winter comparison of TEOM, MiniVol and DustTrak PM10monitors in a woodsmoke environment. *Atmospheric Environment*. 40(2):338–347.

Kistnasamy, E.J., Robins, T.G., Naidoo, R., Batterman, S., Mentz, G.B., Jack, C., & Irusen, E. 2008. The relationship between asthma and ambient air pollutants among primary school students in Durban, South Africa. *Int. J. Environment and Health*. 2(3/4):365–385.

Koistinen, K.J., Edwards, R.D., Mathys, P., Ruuskanen, J., Kunzli, N., & Jantunen, M.J. 2004. Sources of fine particulate matter in personal exposures and residential indoor, residential outdoor and workplace microenvironments in Helsinki phase of the EXPOLIS study. *Scandinavian Journal of Work, Environment & Health*. 30(2):36–46.

Kong, S., Ji, Y., Lu, B., Chen, L., Han, B., Li, Z., & Bai, Z. 2011. Characterization of PM10 source profiles for fugitive dust in Fushun-a city famous for coal. *Atmospheric Environment*. *Pergamon*. 45(30):5351–5365.

Kopperud, R.J., Ferro, A.R., & Hildemann, L.M. 2004. Outdoor Versus Indoor Contributions to Indoor Particulate Matter (PM) Determined by Mass Balance Methods. *Journal of the Air & Waste Management Association*. 54(9):1188–1196.

Korhonen, K., Giannakaki, E., Mielonen, T., Pfüller, A., Laakso, L., Vakkari, V., Baars, H., Engelmann, R., Beukes, J.P., Van Zyl, P.G., Ramandh, A., Ntsangwane, L., Josipovic, M., Tiitta, P., Fourie, G., Ngwana, I., Chiloane, K., & Komppula, M. 2014. Atmospheric Chemistry and Physics Atmospheric boundary layer top height in South Africa: measurements with lidar and radiosonde compared to three atmospheric models. *Atmos. Chem. Phys*. 14:4263–4278.

Kulkarni, P., Baron, P.A. (Paul A., & Willeke, K. 2011. Aerosol measurement : principles, techniques, and applications. Wiley.

Kumar, A., Suresh, ·, & Elumalai, P. 2018. Influence of Road Paving on Particulate Matter Emission and Fingerprinting of Elements of Road Dust. *Archives of Environmental Contamination and Toxicology*. 75:424–435.

Kumar, S., Aggarwal, S.G., Gupta, P.K., & Kawamura, K. 2015. Investigation of the tracers for plastic-enriched waste burning aerosols. *Atmospheric Environment*. *Elsevier Ltd*. 108:49–58.

Kumar, S., Aggarwal, S.G., Sarangi, B., Malherbe, J., Barre, J.P.G., Berail, S., Séby, F., & Donard, O.F.X. 2018. Understanding the Influence of Open-waste Burning on Urban Aerosols using Metal Tracers and Lead Isotopic Composition. *Aerosol and Air Quality Research*. 18:2433–2446.

Kurmi, O.P., Semple, S., Simkhada, P., Smith, W.C.S., & Ayres, J.G. 2010. COPD and chronic bronchitis risk of indoor air pollution from solid fuel: a systematic review and meta-analysis. *Thorax*. *BMJ Publishing Group Ltd*. 65(3):221–8.

Labban, R., Veranth, J.M., Chow, J.C., Engelbrecht, J.L.P., & Watson, J.G. 2004. Size and geographical variation in PM 1 , PM 2.5 and PM 10 : source profiles from soils in the western United States. *Water, Air, and Soil Pollution*. 157:13–31.

Lakes Environmental Software. 2018. WRPLOT View - Air Dispersion Model. Wareloo, Canada.

Language, B., Piketh, S.J., Wernecke, B., & Burger, R. 2016. Household air pollution in South African low-income settlements: a case study. *Transactions on Ecology and The Environment*. 207:1743–3541.

Larson, T., Gould, T., Simpson, C., Liu, L.-J.S., Claiborn, C., & Lewtas, J. 2004. Source Apportionment of Indoor, Outdoor, and Personal PM2.5 in Seattle. Washington, Using Positive Matrix Factorization. *Journal of the Air & Waste Management Association*. 54(9):1175–1187.

Lee, M.-S., Hang, J., Zhang, F., Dai, H., Su, L., & Christiani, D.C. 2012. In-home solid fuel use and cardiovascular disease: a cross-sectional analysis of the Shanghai Putuo study. *Environmental Health*. 11(18).

Lelieveld, J. 2017. Clean air in the Anthropocene. *Faraday Discussions*. 200:693–703.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H.R., Andrews, K.G., Aryee, M., Atkinson, C., Bacchus, L.J., Bahalim, A.N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M.L., Blore, J.D., Blyth, F., Bonner, C., Borges, G., Bourne, R., Boussinesq, M., Brauer, M., Brooks, P., Bruce, N.G., Brunekreef, B., Bryan-Hancock, C., Bucello, C., Buchbinder, R., Bull, F., Burnett, R.T., Byers, T.E., Calabria, B., Carapetis, J., Carnahan, E., Chafe, Z., Charlson, F., Chen, H., Chen, J.S., Cheng, A.T.A., Child, J.C., Cohen, A., Colson, K.E., Cowie, B.C.,

Darby, S., Darling, S., Davis, A., Degenhardt, L., Dentener, F., Des Jarlais, D.C., Devries, K., Dherani, M., Ding, E.L., Dorsey, E.R., Driscoll, T., Edmond, K., Ali, S.E., Engell, R.E., Erwin, P.J., Fahimi, S., Falder, G., Farzadfar, F., Ferrari, A., Finucane, M.M., Flaxman, S., Fowkes, F.G.R., Freedman, G., Freeman, M.K., Gakidou, E., Ghosh, S., Giovannucci, E., Gmel, G., Graham, K., Grainger, R., Grant, B., Gunnell, D., Gutierrez, H.R., Hall, W., Hoek, H.W., Hogan, A., Hosgood, H.D., Hoy, D., Hu, H., Hubbell, B.J., Hutchings, S.J., Ibeanusi, S.E., Jacklyn, G.L., Jasrasaria, R., Jonas, J.B., Kan, H., Kanis, J.A., Kassebaum, N., Kawakami, N., Khang, Y.H., Khatibzadeh, S., Khoo, J.P., Kok, C., Laden, F., Lalloo, R., Lan, Q., Lathlean, T., Leasher, J.L., Leigh, J., Li, Y., Lin, J.K., Lipshultz, S.E., London, S., Lozano, R., Lu, Y., Mak, J., Malekzadeh, R., Mallinger, L., Marcenes, W., March, L., Marks, R., Martin, R., McGale, P., McGrath, J., Mehta, S., Mensah, G.A., Merriman, T.R., Micha, R., Michaud, C., Mishra, V., Hanafiah, K.M., Mokdad, A.A., Morawska, L., Mozaffarian, D., Murphy, T., Naghavi, M., Neal, B., Nelson, P.K., Nolla, J.M., Norman, R., Olives, C., Omer, S.B., Orchard, J., Osborne, R., Ostro, B., Page, A., Pandey, K.D., Parry, C.D.H., Passmore, E., Patra, J., Pearce, N., Pelizzari, P.M., Petzold, M., Phillips, M.R., Pope, D., Pope, C.A., Powles, J., Rao, M., Razavi, H., Rehfuess, E.A., Rehm, J.T., Ritz, B., Rivara, F.P., Roberts, T., Robinson, C., Rodriguez-Portales, J.A., Romieu, I., Room, R., Rosenfeld, L.C., Roy, A., Rushton, L., Salomon, J.A., Sampson, U., Sanchez-Riera, L., Sanman, E., Sapkota, A., Seedat, S., Shi, P., Shield, K., Shivakoti, R., Singh, G.M., Sleet, D.A., Smith, E., Smith, K.R., Stapelberg, N.J.C., Steenland, K., Stöckl, H., Stovner, L.J., Straif, K., Straney, L., Thurston, G.D., Tran, J.H., Van Dingenen, R., Van Donkelaar, A., Veerman, J.L., Vijayakumar, L., Weintraub, R., Weissman, M.M., White, R.A., Whiteford, H., Wiersma, S.T., Wilkinson, J.D., Williams, H.C., Williams, W., Wilson, N., Woolf, A.D., Yip, P., Zielinski, J.M., Lopez, A.D., Murray, C.J.L., & Ezzati, M. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: A systematic analysis for the Global Burden of Disease Study 2010. *The Lancet*. 380(9859):2224–2260.

Lin, H., Murray, M., Cohen, T., Colijn, C., & Ezzati, M. 2009. Effects of smoking and solid-fuel use on COPD, lung cancer, and tuberculosis in China: a time-based, multiple risk factor, modelling study. *Lancet*. 372(9648):1473–1483.

Liu, Q., Liu, Y., & Zhang, M. 2014. Source Apportionment of Personal Exposure to Carbonyl Compounds and BTEX at Homes in Beijing, China. *Aerosol and Air Quality Research*. 14:330–337.

Liu, Y., Xing, J., Wang, S., Fu, X., & Zheng, H. 2018. Source-specific speciation profiles of PM2.5 for heavy metals and their anthropogenic emissions in China. *Environmental Pollution*. *Elsevier*. 239:544–553.

Liu, Y., Zhang, W., Bai, Z., Yang, W., Zhao, X., Han, B., & Wang, X. 2017. China Source Profile Shared Service (CSPSS): The Chinese PM 2.5 Database for Source Profiles. *Aerosol and Air Quality Research*. 17:1501–1514.

Liu, Y., Zhang, W., Yang, W., Bai, Z., & Zhao, X. 2018. Chemical Compositions of PM 2.5 Emitted from Diesel Trucks and Construction Equipment. *Aerosol Science and Engineering*. 2:51–60.

Maenhaut, W., Salma, I., Cafmeyer, J., Annegarn, H.J., & Andreae, M.O. 1996. Regional atmospheric aerosol composition and sources in the eastern Transvaal, South Africa, and impact of biomass burning. *Journal of Geophysical Research Atmospheres*. *Blackwell Publishing Ltd*. 101(19):23631–23650.

Maenhaut, W., Schwarz, J., Cafmeyer, J., & Annegarn, H.J. 2002. Study of elemental mass size distributions at Skukuza, South Africa, during the SAFARI 2000 dry season campaign. *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*. 189(1–4):254–258.

Magill, P.L. 1949. The Los Angeles Smog Problem. *Industrial & Engineering Chemistry*. 41(11):2476–2486.

Mahalanabis, D., Gupta, S., Paul, D., Gupta, A., Lahiri, M., & Khaled, M.A. 2002. Risk factors for pneumonia in infants and young children and the role of solid fuel for cooking: A case-control study. *Epidemiology and Infection*. 129(1):65–71.

Malvern PANalytical Ltd. 2010. SuperQ Software Version 5.0. Netherlands.

Martuzevicius, D., Grinshpun, S.A., Lee, T., Hu, S., Biswas, P., Reponen, T., & LeMasters, G. 2008. Traffic-related PM2.5 aerosol in residential houses located near major highways: Indoor versus outdoor concentrations. *Atmospheric Environment*. *Pergamon*. 42(27):6575–6585.

Mason, B. 1966. Principles of Geochemistry. 3rd ed. Wiley: New York.

Matawle, J.L., Pervez, S., Dewangan, S., Shrivastava, A., Tiwari, S., Pant, P., Kanti Deb, M., & Pervez, Y. 2015. Characterization of PM 2.5 Source Profiles for Traffic and Dust Sources in Raipur, India. *Aerosol and Air Quality Research*. 15:2537–2548.

Matawle, J.L., Pervez, S., Dewangan, S., Tiwari, S., Singh Bisht, D., & Pervez, Y.F. 2014. PM 2.5 Chemical Source Profiles of Emissions Resulting from Industrial and Domestic Burning Activities in India. *Aerosol and Air Quality Research*. 14:2051–2066.

Matooane, M., John, J., Oosthuizen, R., & Binedell, M. 2004. Vulnerability of South African Communities to Air Pollution. , in: 8th World Congress on Environmental Health. Durban, South Africa. . Durban, South Africa.

McCracken, J.P., Wellenius, G.A., Bloomfield, G.S., Brook, R.D., Tolunay, H.E., Dockery, D.W., Rabadan-Diehl, C., Checkley, W., & Rajagopalan, S. 2012. Household Air Pollution from Solid Fuel Use:

Evidence for Links to CVD. *Global Heart*. *Elsevier*. 7(3):223–234.

McMurry, P.H. 2000. A review of atmospheric aerosol measurements. *Atmospheric Environment*. *Pergamon*. 34(12–14):1959–1999.

McNamara, M.L., Noonan, C.W., & Ward, T.J. 2011. Correction factor for continuous monitoring of wood smoke fine particulate matter. *Aerosol Air Qual Res.* 11(3):315–322.

Mentz, G., Robins, T.G., Batterman, S., & Naidoo, R.N. 2018. Acute respiratory symptoms associated with short term fluctuations in ambient pollutants among schoolchildren in Durban, South Africa. *Environmental Pollution*. *Elsevier*. 233:529–539.

Minguillón, M.C., Schembari, A., Triguero-Mas, M., de Nazelle, A., Dadvand, P., Figueras, F., Salvado, J.A., Grimalt, J.O., Nieuwenhuijsen, M., & Querol, X. 2012. Source apportionment of indoor, outdoor and personal PM2.5 exposure of pregnant women in Barcelona, Spain. *Atmospheric Environment*. *Pergamon*. 59:426–436.

Mishra, V. 2003. Effect of Indoor Air Pollution from Biomass Combustion on Prevalence of Asthma in the Elderly. *Environmental Health Perspectives*. 111(1):71–77.

Misra, A., Longnecker, M.P., Dionisio, K.L., Bornman, R.M.S., Travlos, G.S., Brar, S., & Whitworth, K.W. 2018. Household fuel use and biomarkers of inflammation and respiratory illness among rural South African Women. *Environmental Research*. *Academic Press*. 166:112–116.

Molnár, P., Johannesson, S., & Quass, U. 2014. Source Apportionment of PM 2.5 Using Positive Matrix Factorization (PMF) and PMF with Factor Selection. *Aerosol and Air Quality Research*. 14:725–733.

Morakinyo, O.M., Adebowale, A.S., Mokgobu, M.I., & Mukhola, M.S. 2017. Health risk of inhalation exposure to sub-10 µm particulate matter and gaseous pollutants in an urban-industrial area in South Africa: an ecological study. *BMJ Open*. 7:13941.

Moyers, J.L., Ranweiler, L.E., Hopf, S.B., & Korte, N.E. 1975. Standard Methods for the Examination of Water and Waste-water. , Proc. Soc. Water Treat. Exam. Van Nostrand-Reinhold.

Mroz, E.J. & Zoller, W.H. 1975. Composition of Atmospheric Particulate Matter from the Eruption of Heimaey, Iceland. *Science*. 190(4213):461–464.

Muller, E., Diab, R.., Binedell, M., & Hounsome, R. 2003. Health risk assessment of kerosene usage in an informal settlement in Durban, South Africa. *Atmospheric Environment*. *Pergamon*. 37(15):2015–2022.

Nagpure, A.S., Ramaswami, A., & Russell, A. 2015. Characterizing the Spatial and Temporal Patterns of Open Burning of Municipal Solid Waste (MSW) in Indian Cities. *Environmental Science & Technology*. 49(21):12904–12912.

Naidoo, R.N., Chb, M.B., Robins, T.G., Batterman, S., Mentz, G., & Jack, C. 2013. Ambient pollution and respiratory outcomes among schoolchildren in Durban, South Africa. *SAJCH*. 7(4):127–134.

Naiker, Y., Diab, R.D., Zunckel, M., & Hayes, E.T. 2012. Introduction of local Air Quality Management in South Africa: Overview and challenges. *Environmental Science and Policy*. *Elsevier Ltd*. 17:62–71.

Narayan, T. 1990. Health Impact of Bhopal Disaster : An Epidemiological Perspective. *Economic and Political Weekly*. 25(34):1905–1914.

Nemery, B., Hoet, P.H.M., & Nemmar, A. 2001. The Meuse Valley fog of 1930: an air pollution disaster. *The Lancet*. 357:704–708.

Ni, H., Tian, J., Wang, X., Wang, Q., Han, Y., Cao, J., Long, X., Chen, L.-W.A., Chow, J.C., Watson, J.G., Huang, R.-J., & Dusek, U. 2017. PM2.5 emissions and source profiles from open burning of crop residues. *Atmospheric Environment*. *Pergamon*. 169:229–237.

NIOSH. 1998. Particulates not otherwise regulated, Respirable definition. 4th ed. , in: Manual of Analytical Methods.

Niu, J., Lu, B.M.K., & Tung, T.C.W. 2002. Instrumentation issue in indoor air quality measurements: The case with respirable suspended particulates. *Indoor and Built Environment*. 11(3):162–170.

Nkosi, V., Wichmann, J., & Voyi, K. 2015. Mine dumps, wheeze, asthma, and rhinoconjunctivitis among adolescents in South Africa: any association? *International Journal of Environmental Health Research*. 25(6):583–600.

Nkosi, V., Wichmann, J., & Voyi, K. 2017. Indoor and outdoor PM 10 levels at schools located near mine dumps in Gauteng and North West Provinces, South Africa. *BMC Public Health*. 17:42.

Norman, R., Barnes, B., Mathee, A., Bradshaw, D., & Group, and the S.A.C.R.A.C. 2007. Estimating the burden of disease attributable to indoor air pollution from household use of solid fuels in South Africa in 2000. *South African Medical Journal*. 97(8):764.

Norman, R., Bradshaw, D., Lewin, S., Cairncross, E., Nannan, N., Vos, T., & South African Comparative Risk Asse, S.A.C.R.A.C. 2010. Estimating the Burden of Disease Attributable to Four Selected Environmental Risk Factors in South Africa. *Reviews on Environmental Health*. *De Gruyter*. 25(2):87–120.

Norman, R., Cairncross, E., Witi, J., Bradshaw, D., & South African Comparative Risk Assessment Collaborating Group. 2007. Estimating the burden of disease attributable to urban outdoor air pollution in South Africa in 2000. *South African Medical Journal*. 97(7):782–790.

North-West University. 2018. Research ethics policy.

North-West University. 2019. Policy and rules for research ethics.

Occupational Health and Safety Administration. 1999. OSHA Technical Manual.

Olawoyin, R. 2018. Adverse Human Health Impacts in the Anthropocene. *Environmental health insights*. *SAGE Publications*. 12:1–5.

Osman, L.M., Douglas, J.G., Garden, C., Reglitz, K., Lyon, J., Gordon, S., & Ayres, J.G. 2007. Indoor air quality in homes of patients with chronic obstructive pulmonary disease. *American Journal of Respiratory and Critical Care Medicine*. 176(5):465–472.

Padhi, B.K. & Padhy, P.K. 2008. Domestic Fuels, Indoor Air Pollution, and Children's Health. *Annals of the New York Academy of Sciences*. *John Wiley & Sons, Ltd (10.1111)*. 1140(1):209–217.

Palmgren, F., Wåhlin, P., Kildesø, J., Afshari, A., & Fogh, C.L. 2003. Characterisation of particle emissions from the driving car fleet and the contribution to ambient and indoor particle concentrations. *Physics and Chemistry of the Earth*. *Pergamon*. 28:327–334.

Pant, P. & Harrison, R.M. 2012. Critical review of receptor modelling for particulate matter: A case study of India. *Atmospheric Environment*. *Pergamon*. 49:1–12.

Park, D., Oh, M., Yoon, Y., Park, E., & Lee, K. 2012. Source identification of PM10 pollution in subway passenger cabins using positive matrix factorization. *Atmospheric Environment*. *Pergamon*. 49:180–185.

Patil, R.S., Kumar, R., Menon, R., Shah, M.K., & Sethi, V. 2013. Development of particulate matter speciation profiles for major sources in six cities in India. *Atmospheric Research*. *Elsevier*. 132–133:1–11.

Peltzer, K., Peltzer, & Karl. 2011. Determinants of Exposure to Second-Hand Tobacco Smoke (SHS) among Current Non-Smoking In-School Adolescents (aged 11–18 years) in South Africa: Results from the 2008 GYTS Study. *International Journal of Environmental Research and Public Health*. *Molecular Diversity Preservation International*. 8:3553–3561.

Perez-Padilla, R., Schilmann, A., & Riojas-Rodriguez, H. 2010. Respiratory health effects of indoor air pollution. *International Journal of Tuberculosis and Lung Disease*. *International Union Against*

Tuberculosis and Lung Disease. 14(9):1079–1086.

Pernigotti, D., Belis, C.A., & Spanó, L. 2016. SPECIEUROPE: The European data base for PM source profiles. *Atmospheric Pollution Research*. 7:307–314.

Pervez, S., Dubey, N., Watson, J.G., Chow, J., & Pervez, Y. 2012. Impact of Different Household Fuel Use on Source Apportionment Results of House-Indoor RPM in Central India. *Aerosol and Air Quality Research*. 12:49–60.

Pey, J., Pérez, N., Cortés, J., Alastuey, A., & Querol, X. 2013. Chemical fingerprint and impact of shipping emissions over a western Mediterranean metropolis: Primary and aged contributions. *Science of The Total Environment. Elsevier*. 463–464:497–507.

Pietrodangelo, A., Salzano, R., Rantica, E., & Perrino, C. 2013. Characterisation of the local topsoil contribution to airborne particulate matter in the area of Rome (Italy). Source profiles. *Atmospheric Environment. Pergamon*. 69:1–14.

Po, J.Y.T., FitzGerald, J.M., & Carlsten, C. 2011. Respiratory disease associated with solid biomass fuel exposure in rural women and children: systematic review and meta-analysis. *Thorax. BMJ Publishing Group Ltd*. 66(3):232–9.

Pope, C.A. 2000. Review: Epidemiological Basis for Particulate Air Pollution Health Standards. *Aerosol Science & Technology*. 32(1):4–14.

Pope, D.P., Mishra, V., Thompson, L., Siddiqui, A.R., Rehfuess, E.A., Weber, M., & Bruce, N.G. 2010. Risk of Low Birth Weight and Stillbirth Associated With Indoor Air Pollution From Solid Fuel Use in Developing Countries. *Epidemiologic Reviews. Oxford University Press*. 32(1):70–81.

Ramachandran, G., Adgate, J.L., Hill, N., Sexton, K., Pratt, G.C., & Bock, D. 2000. Comparison of short-term variations (15-minute averages) in outdoor and indoor PM2.5concentrations. *Journal of the Air and Waste Management Association*. 50(7):1157–1166.

Reddy, P., Naidoo, R.N., Robins, T.G., Mentz, G., Li, H., London, S.J., & Batterman, S. 2012. *GSTM1* and *GSTP1* gene variants and the effect of air pollutants on lung function measures in South African children. *American Journal of Industrial Medicine. John Wiley & Sons, Ltd*. 55(12):1078–1086.

Reddy, P., Zuma, K., Jonas, K., & Sewpaul, R. 2015. South African journal of obstetrics and gynaecology. : Suid-Afrikaanse tydskrif vir obstetrie en ginekologie. , South African Medical Journal.

Reff, A., Eberly, S.I., & Bhave, P. V. 2007. Receptor Modeling of Ambient Particulate Matter Data Using Positive Matrix Factorization: Review of Existing Methods. *Journal of the Air & Waste Management*

Association. 57(2):146–154.

Rehfuess, E.A., Bruce, N.G., & Smith, K.R. 2011. Solid Fuel Use: Health Effect. , in: Encyclopedia of Environmental Health. . pp. 150–161.

Rehfuess, E.A., Tzala, L., Best, N., Briggs, D.J., & Joffe, M. 2009. Solid fuel use and cooking practices as a major risk factor for ALRI mortality among African children. *Journal of Epidemiology and Community Health*. 63(11):887–892.

Rollin, H.B., Mathee, A., Bruce, N., Levin, J., & von Schirnding, Y.E.R. 2004. Comparison of indoor air quality in electrified and un-electrified dwellings in rural South African villages. *Indoor Air*. *John Wiley & Sons, Ltd (10.1111)*. 14(3):208–216.

Sai, S., Ho, H., Wang, G., & Wang, K. 2015. Characteristics of PM2.5 emitted from different cooking activities in China. *Atmospheric Research*. 166:83–91.

Samara, C., Kouimtzis, T., Tsitouridou, R., Kanias, G., & Simeonov, V. 2003. Chemical mass balance source apportionment of PM10 in an industrialized urban area of Northern Greece. *Atmospheric Environment. Pergamon*. 37(1):41–54.

Sanyal, D.K. & Maduna, M.E. 2000. Possible relationship between indoor pollution and respiratory illness in an Eastern Cape community. *South African Journal of Science*. 96:94–96.

Saraga, D.E., Maggos, T.E., Sfetsos, A., Tolis, E.I., Andronopoulos, S., Bartzis, J.G., & Vasilakos, C. 2010. PAHs sources contribution to the air quality of an office environment: experimental results and receptor model (PMF) application. *Air Quality, Atmosphere and Health*. 3:225–234.

Scheifinger, H. & Held, G. 1997. Aerosol behaviour on the South African highveld. *Atmospheric Environment. Pergamon*. 31(21):3497–3509.

Schmidl, C., Bauer, H., Dattler, A., Hitzenberger, R., Weissenboeck, G., Marr, I.L., & Puxbaum, H. 2008. Chemical characterisation of particle emissions from burning leaves. *Atmospheric Environment. Pergamon*. 42(40):9070–9079.

Schmidl, C., Marr, I.L., Caseiro, A., Kotianová, P., Berner, A., Bauer, H., Kasper-Giebl, A., & Puxbaum, H. 2008. Chemical characterisation of fine particle emissions from wood stove combustion of common woods growing in mid-European Alpine regions. *Atmospheric Environment. Pergamon*. 42(1):126–141.

Schrenk, H.H., Heimann, H., Clayton, G.D., Gafafer, W.M., & Wexler, H. 1949. Air Pollution in Donora, Pa. Epidemiology of the Unusual Smog Episode of October 1948. Preliminary Report. , Public Health Bulletic.

Scorer, R.S. 1954. Smog. *Science Progress (1933-)1*. 42(167):396–405.

Seigneur, C., Pai, P., Hopke, P.K., & Grosjean, D. 1999. Modeling Atmospheric Particulate Matter. *Environmental Science & Technology*. :80–86.

Seinfeld, J.H., Pandis, S.N., & Πανδής, Σ.N. 1963-. 2006. Atmospheric chemistry and physics : from air pollution to climate change. J. Wiley.

Sensidyne. 1999. Personal cyclone sampler. (PNº 7013376).

Sensidyne. 2003. Gilian Cyclone & Cassette Holder Assembly Kit Document No. F-PRO-1247 (Revision C).

Sensidyne. 2019. Gilian Connect Pump and Sampling Management Software. St. Petersburg. USA.

Shandilya, K. & Kumar, A. 2014. Carbon speciation of exhaust particulate matter of public transit buses running on alternative fuels. *Fuel*. *Elsevier*. 115:678–684.

Shen, M., Chapman, R.S., Vermuelen, R., Tian, L., Zheng, T., Chen, B.E., Engels, E.A., He, X., Blair, A., & Lan, Q. 2009. Coal use, stove improvement, and adult pneumonia mortality in Xuanwei, China: A retrospective cohort study. *Environmental Health Perspectives*. 117(2):261–266.

Shen, Z., Sun, J., Cao, J., Zhang, L., Zhang, Q., Lei, Y., Gao, J., Huang, R.-J., Liu, S., Huang, Y., Zhu, C., Xu, H., Zheng, C., Liu, P., & Xue, Z. 2016. Chemical profiles of urban fugitive dust PM2.5 samples in Northern Chinese cities. *Science of The Total Environment*. *Elsevier*. 569–570:619–626.

Shenfeld, L. 1970. Meteorological aspects of air pollution control. *Atmosphere*. 8(1):3–13.

Shezi, B., Jafta, N., Sartorius, B., & Naidoo, R.N. 2017. Developing a predictive model for fine particulate matter concentrations in low socio-economic households in Durban, South Africa. *Indoor Air*. *John Wiley & Sons, Ltd (10.1111)*. 28(2):228–237.

Shezi, B. & Wright, C.Y. 2018. Household air pollution exposure and respiratory health outcomes: a narrative review update of the South African epidemiological evidence. *Clean Air Journal*. *National Association for Clean Air*. 28(1):43–56.

Shin, S.H. & Jo, W.K. 2012. Volatile organic compound concentrations, emission rates, and source apportionment in newly-built apartments at pre-occupancy stage. *Chemosphere*. *Pergamon*. 89(5):569–578.

Shirinde, J., Wichmann, J., & Voyi, K. 2014. Association between wheeze and selected air pollution

sources in an air pollution priority area in South Africa: a cross-sectional study. *Environmental Health*. *BioMed Central*. 13(1):32.

Shirinde, J., Wichmann, J., & Voyi, K. 2015. Allergic rhinitis, rhinoconjunctivitis and hayfever symptoms among children are associated with frequency of truck traffic near residences: a cross sectional study. *Environmental Health*. *BioMed Central*. 14(1):84.

Shrivastava, A. & Gupta, V.B. 2011. Methods for the determination of limit of detection and limit of quantitation of the analytical methods. *Chronicles of Young Scientists*. 2(1):21–25.

Simon, H., Beck, L., Bhave, P. V, Divita, F., Hsu, Y., Luecken, D., David Mobley, J., Pouliot, G.A., Reff, A., Sarwar, G., & Strum, M. 2010. The development and uses of EPA's SPECIATE database. *Atmospheric Pollution Research*. 1:196–206.

Smith, K.R. 1993. Fuel combustion, air pollution, and health: The situation in developing countries. *Annual Review Energy Environment*. 18:529–66.

Snyder, L.P. 1994. "The Death-Dealing Smog over Donora , Pennsylvania": Industrial Air Pollution , Public Health Policy , and the Politics of Expertise , 1948-1949. *Special Issue on Technology, Pollution, and the Environment*. 18(1):117–139.

Sonntag, D.B., Baldauf, R.W., Yanca, C.A., & Fulper, C.R. 2014. Particulate matter speciation profiles for light- duty gasoline vehicles in the United States. *Journal of the Air & Waste Management Association*. 64(5):529–545.

South Africa. 1996. Constitution of the Republic of South Africa Act 108 of 1996. *Government Gazette*.

South Africa. 1997. Atmospheric Pollution Prevention Act. *Government Gazette*.

South Africa. 1998a. White Paper on the Environmental Management Policy of the Republic of South Africa. *Government Gazette*. 395(December):3–89.

South Africa. 1998b. National Environmental Management Act No. 107 of 1998. *Government Gazette*. (401).

South Africa. 2000. White Paper on Integrated Pollution and Waste Management in South Africa. *Government Gazette*. 417(20978):3–81.

South Africa. 2004. National Environment Management: Air Quality Act, 2004 (Act No. 39 of 2004). *Government Gazette*. 476(27318):2–56.

South Africa. 2006. National Environmental Management: Air Quality Act (39/2004): Declaration of the Vaal Triangle Air-shed. *Government Gazette*. 28732(10505):6–7.

South Africa. 2007a. The 2007 National Framework for Air Quality Management in the Republic of South Africa. *Government Gazette*. 30284(1138):3–101.

South Africa. 2007b. National Environmental Management: Air Quality Act (39/2004): Declaration of the Highveld priority area in terms of section 18 (1). *Government Gazette*. 30518(1123):3.

South Africa. 2009a. National Environmental Management: Air Quality Act (39/2004): Vaal Triangle Air-Shed Priority Area Air Quality Management Plan. *Government Gazette*. 10505(32263).

South Africa. 2009b. National Environmental Management: Air Quality Act (39/2004): Regualtions for Implementing and Enforcing the Vall Triangle Air-Shed Priority Area Air Quality Management Plan. *Government Gazette*. 10505(32254):41–47.

South Africa. 2009c. National Environmental Management: Air Quality Act 39 of 2004 - National ambient air quality standards. *Government Gazette*. 1210(32816):3–5.

South Africa. 2010a. National Environmental Management Act, 1998 (Act No. 107 of 1998): Environmental Impact Assessment Regulations. *Government Gazette*. 540(33306):3–79.

South Africa. 2010b. National Environmental Management: 1998 (Act No. 107 of 1998): Model Air Quality Management By-law for Adoption and Adaptation by Municipalities. *Government Gazette*. (33342):3–50.

South Africa. 2010c. National Environmental Management , 1998 (Act No. 107 of 1998): Commencement of Environmental Impact Assessment Regulations, 2010. *Government Gazette*. (33411):8.

South Africa. 2010d. National Environmental Management Act, 1998 (Act No. 107 of 1998): Commencement of Environmental Management Framework Regulations, 2010. *Government Gazette*. (33411):9.

South Africa. 2012a. National Environmental Mangement: Air Quality Act (39/2004): Highveld Priority Area Air Quality Management Plan. *Government Gazette*. 561(35027):3–278.

South Africa. 2012b. National Environmental Management: Air Quality Act (39/2004): Declaration of the Waterberg National Priority Area. *Government Gazette*. (35435):60–61.

South Africa. 2012c. National Environmental Management: Air Quality Act (39/2004): National ambient air quality standard for particulate matter with aerodynamic diameter less than 2.5 micron metres (PM 2.5).

Government Gazette. 564(35463):7–26.

South Africa. 2013a. National Environmental Management: Air Quality Act (39/2004): Regulation prescribing the format of th eatmospheric impact report. *Government Gazette*. 580(36904):9–33.

South Africa. 2013b. National Environmental Management: Air Quality Act (39/2004): Declaration of a small boiler as a controlled emitter and establishment of emission standards. *Government Gazette*. 581(36973).

South Africa. 2013c. National Environmental Management: Air Quality Act (39/2004): National Dust Regulations. *Government Gazette*. 581(36974):4–8.

South Africa. 2013d. National Environmental Management: Air Quality Act, 2004 (39/2004): List of activities which result in atmospheric emissions which have or may have a significant detrimental effect on the environmnet, including health, social conditions, economic conditio. *Government Gazette*. 581(37054):3–63.

South Africa. 2013e. National Environmnetal Management: Air Quality Act (39/2004): Amendment to the 2007 National Framework for Air Quality Mangement in the Republic of South Africa. *Government Gazette*. 581(37078):3–105.

South Africa. 2014a. National Environmental Management Act: Air Quality Act (39/2004): Declaration of temporary asphalt plants as a controlled emitter and establishment of emissions standards. *Government Gazette*. 585(37461):18–28.

South Africa. 2014b. National Environmental Management: Air Quality Amendment Act, 2014. *Government Gazette*. 587(37666):2–17.

South Africa. 2014c. National Environmental Management: Air Quality Act (39/2004): Regulations regarding Air Dispersion Modelling. *Government Gazette*. 589(37804):3–75.

South Africa. 2014d. National Environmental Management: Air Quality Act (39/2004): Draft National Air Quality Appeal Regulations. *Government Gazette*. 392(38122):3–8.

South Africa. 2014e. National Environmental Management Act (107/1998): Environmental Impact Assessment Regulations, 2014. *Government Gazette*. 594(38282):3–74.

South Africa. 2014f. Listing notice 1: List of activities and competent authorities identified in terms of sections 24 (2) and 24 D. *Government Gazette*. Notice 983(38282):75, 4 Dec.

South Africa. 2014g. Listing notice 2: List of activities and competent authorities identified in terms of

sections 24 (2) and 24 D. *Government Gazette*. Notice 984(38282):106, 4 Dec.

South Africa. 2014h. Listing notice 3: List of activities and competent authorities identified in terms of sections 24 (2) and 24 D. *Government Gazette*. Notice 985(38282):120, 4 Dec.

South Africa. 2014i. National Environmental Management: Air Quality Act 39 of 2004. *Government Gazette*.

South Africa. 2015a. National Environmental Management: Air Quality Act (39/2004): National Atmospheric Emission Reporting Regulations. *Government Gazette*. 598(38633):4–11.

South Africa. 2015b. National Environmental Management: Air Quality Act (39/2004): Amendments to the Regulations Prescribing the Format of the Atmospheric Impact Report, 2013. *Government Gazette*. 598(38633):12–13.

South Africa. 2015c. National Environmental Management: Air Quality Act (39/2004): Draft National Greenhouse Gas Emission Reporting Regulations. *Government Gazette*. 600(38857):6–44.

South Africa. 2015d. National Environmental Management: Air Quality Act (39/2004): Draft regulations prescribing the atmospheric emission licence processing fee. *Government Gazette*. 600(38863):45–48.

South Africa. 2015e. National Environmental Management: Air Quality Act (39/2004): Amendments of the list of activities which result in atmospheric emission which have or may have a significant detrimental effect on the environment, including health, social conditions, econo. *Government Gazette*. 600(38863):49–54.

South Africa. 2015f. National Environmental Management Act: Air Quality Act, (39/2004): Declaration of a Small-Scale Char and Small- Scale Charcoal Plants as controlled emitters and establishment of emmission standards. *Government Gazette*. 603(39220):24–34.

South Africa. 2015g. National Environmental Management Act (107/1998): Regulations pertaining to the Financial Provision for Prospecting, Exploration, Mining or Production Operations. *Government Gazette*. 605(39425):4–45.

South Africa. 2015h. National Environmental Management: Air Quality Act (39/2004):: Waterberg Bojanala Priority Area Air Quality Management Plan. *Government Gazette*. 606(39489):4–272.

South Africa. 2016a. National Environmental Management: Air Quality Act (39/2004): Regulations prescribing the atmospheric emission licence processing fee. *Government Gazette*. 309(39805):4–7.

South Africa. 2016b. National Environmental Management: Air Quality Act (39/2004): Regulations for

the procedure and criteria to be followed in the determination of an administrative fine in terms of section 22A of the Act. *Government Gazette*. 609(39833):4–8.

South Africa. 2016c. National Environmental Management Act (107/1998): Air quality offsets guideline. *Government Gazette*. 609(39833):8–26.

South Africa. 2016d. Draft Strategy to address Air Pollution in dense low-income settlements: For comments. *Government Gazette*. 612(40088):1008–1053.

South Africa. 2016e. National Environmental Management Act (107/1998): Proposed amendments to Financial Provisioning Regulations, 2015. *Government Gazette*. 615(40265):4–7.

South Africa. 2017a. National Environmental Management: Air Quality Act (39/2004): National Greenhouse Gas Emission Reporting Regulations. *Government Gazette*. 622(40762):4–22.

South Africa. 2017b. National Environmental Management Act (107/1998) – Amendment of the environmental impact assessment regulations listing notice 3 of 2014. *Government Gazette*. 622(40772):57–193.

South Africa. 2017c. National Environmental Management Act (107/1998) – Amendment of the environmental impact assessment regulations listing notice 2 of 2014. *Government Gazette*. 40772(622):194–210.

South Africa. 2017d. National Environmental Management Act (107/1998) – Amendments to the environmental impact assessment regulations, 2014. *Government Gazette*. 622(40772):211–276.

South Africa. 2017e. National Environmental Management Act (107/1998) – Amendment of the environmental impact assessment regulations listing notice 1 of 2014. *Government Gazette*. 622(40772):277–318.

South Africa. 2017f. National Environmental Management Act (107/1998): Procedure to be followed in applying for Environmental Authorisation for large scale Wind and Solar Photovoltaic Development. *Government Gazette*. 622(40785):17–21.

South Africa. 2017g. National Environmental Management Act (107/1998): Notice of intention to adopt Gauteng Provincial Environmental Management Framework (GPEMF) Standards and Exclusion of Activities. *Government Gazette*. 622(40785):22–71.

South Africa. 2017h. National Environmental Management Act (107/1998): Proposed regulations to phase-out the use of persistent organic pollutants. *Government Gazette*. 624(40954):4–8.

South Africa. 2017i. National Environmental Management Act (107/1998): Regulations relating to the procedure to be followed and criteria to be considered when determining an appropriate fine in terms of section 24G. *Government Gazette*. 625(40994):4–17.

South Africa. 2017j. National Environmental Management: Air Quality Act (39/2004): Declaration of Greenhouse Gases as priority air Pollutants. *Government Gazette*. 625(40996):65–69.

South Africa. 2017k. National Environmental Management: Air Quality Act (39/2004): National Pollution Prevention Plans Regulations. *Government Gazette*. 625(40996):81–87.

South Africa. 2018a. National Environmental Management Act (107/1998): National guideline on minimum information Requirements for Preparing Environmental Impact Assessments for Mining Activities that Require Environmental Authorisation. *Government Gazette*. 632(41432):19–96.

South Africa. 2018b. National Environmental Management Act (107/1998): Amendment to the regulations pertaining to the Financial Provision for prospecting, exploration, mining or production operations. *Government Gazette*. 634(41584):4–5.

South Africa. 2018c. National Environmental Management: Air Quality Act (39/2004): Amendment of the National Pollution Prevention Plans Regulations, 2017. *Government Gazette*. 635(41642):4–5.

South Africa. 2018d. National Environmental Management: Air Quality Act (39/2004): Notice of Intention to Amend the List of Activities which result in Atmospheric Emission which have or may have a significant detrimental effect on the environment, including health, social con. *Government Gazette*. 635(41650):39–53.

South Africa. 2018e. National Environmental Management: Air Quality Act (39/2004): Draft National Dust Control Regulations. *Government Gazette*. 635(41650):54–60.

South Africa. 2018f. National Environmental Management: Air Quality Act (39/2004): Notice of intention to amend the 2012 National Framework for Air Quality Management in the Republic of South Africa. *Government Gazette*. 635(41650):61–173.

South Africa. 2018g. Climate Change Bill, 2018: For public comment. *Government Gazette*. Notice 580(41689):4, 8 Jun.

South Africa. 2018h. National Environmental Management Act (107/1998): Corrections to the Environmental Impact Assessment Regulations and Listing notices, 2014. *Government Gazette*. 637(41766):16–18.

South Africa. 2018i. National Environmental Management Act (107/1998): Proposed Regulations to

Phase-out the use of Persistent Organic Pollutants. *Government Gazette*. 637(41790):4–8.

South Africa. 2019. National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004) Strategy to address air pollution in dense low-income settlements. *Government Gazette*. (42464):42–87.

South African Weather Service. 2018. Climate Data.

Statistics South Africa. 2011. Statistics release, Census 2011. Pretoria.

Steffen, W., Grinevald, J., Crutzen, P., & Mcneill, J. 2011. The Anthropocene: conceptual and historical perspectives. *Philosophical Transactions of the Royal Society*. 369:842–867.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., & Sörlin, S. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science*. 347(6223):736.

Suryawanshi, S., Chauhan, A.S., Verma, R., & Gupta, T. 2016. Identification and quantification of indoor air pollutant sources within a residential academic campus. *Science of The Total Environment*. *Elsevier*. 569–570:46–52.

Tachakra, S. 1989. The Bhopal Disaster: Lessons for Developing Countries. *Environmental Conservation*. 16(1):65–66.

Thabethe, N.D.L., Christoffel Engelbrecht, J., Yael Wright, C., & Aletta Oosthuizen, M. 2014. Human health risks posed by exposure to PM10 for four life stages in a low socio-economic community in South Africa. *Pan African Medical Journal*. 18.

Thé, J.L., Thé, C.L., & Johnson, M.A. 2016. User Guide Wind and Rain Rose Plots for Meteorological Data WRPLOT View TM. Lakes Environmental Software: Waterloo, Ontario, Canada.

Thorpe, A. 2007. Assessment of personal direct-reading dust monitors for the measurement of airborne inhalable dust. *Annals of Occupational Hygiene*. 51(1):97–112.

Thorpe, A. & Harrison, R.M. 2008. Sources and properties of non-exhaust particulate matter from road traffic: A review. *Science of the Total Environment*. 400(1–3):270–282.

Thurston, G.D. & Lioy, P.J. 1987. Receptor modeling and aerosol transport. *Atmospheric Environment (1967)*. *Elsevier*. 21(3):687–698.

Tian, Y.-Z., Chen, J.-B., Zhang, L.-L., Du, X., Wei, J.-J., Fan, H., Xu, J., Wang, H.-T., Guan, L., Shi, G.-

L., & Feng, Y.-C. 2017. Source profiles and contributions of biofuel combustion for PM2.5, PM10 and their compositions, in a city influenced by biofuel stoves. *Chemosphere*. *Pergamon*. 189:255–264.

TIBCO Software Inc. 2017. Statistica, Version 13.

TSI Incorporated. 2010. Model 8520 DUSTTRAK Aerosol Monitor: Operation and Service Manual.

TSI Incorporated. 2012a. Sidepak™ Personal Aerosol Monitor Model AM510.

TSI Incorporated. 2012b. DustTrak II Aerosol Monitor Theory of Operation: Application Note EXPMN-001.

TSI Incorporated. 2013. Rationale for Programming a Photometer Calibration Factor (Pcf) of 0.38 for Ambient Monitoring. (EXPMN-007 Rev. A (8/26/2013)):1–4.

TSI Incorporated. 2014. DUSTTRAK II Aerosol Monitor Model 8530/8531/8532/8530EP: Operation and Service Manual.

TSI Incorporated. 2019. TrakPro. Shoreview, USA.

Tunno, B.J., Dalton, R., Cambal, L., Holguin, F., Lioy, P., & Clougherty, J.E. 2016. Indoor source apportionment in urban communities near industrial sites. *Atmospheric Environment*. *Pergamon*. 139:30–36.

Tyson, P.D., Garstang, M., Swap, R., Kallberg, P., & Edwards, M. 1996. An air transport climatology for subtropical southern Africa. *International Journal of Climatology*. *John Wiley & Sons, Ltd*. 16(3):265–291.

Tyson, P.D. & Preston-Whyte, R.A. 2004. The Weather and Climate of Southern Africa. 2nd ed. Oxford University Press South Africa: Cape Town.

U.S.EPA. 2006. SPECIATE 4.0 Speciation Database Development Documentation.

U.S.EPA. 2009. SPECIATE 4.2 Speciation Database Development Documentation.

U.S.EPA. 2011. SPECIATEE 4.3: Addendum to SPECIATE 4.2 Speciation Database Development Documentation.

U.S.EPA. 2014. SPECIATE Version 4.4 Database Development Documentation.

U.S.EPA. 2016. SPECIATE Version 4.5 Database Development Documentation.

U.S.EPA. 2019. SPECIATE 5.0: Speciation Database Development Documentation.

United Nations. 1979. 1979 Convention on long-Range Transboundary Air Pollution.

United Nations. 1984. Protocol to the 1979 Convention on Long-range Transboundary Air Pollution on Long-term Financing of the Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) . Geneva, 28 September 1984.

United Nations. 1985. Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30 per cent. Helsinki, 8 July 1985.

United Nations. 1988. Protocol to the 1979 Convention on long-range transboundary air pollution concerning the control of emissions of nitrogen oxides or their trans fluxes. Sofia, 31 October 1988. (October).

United Nations. 1991. Protocol to the 1979 Convention on Long-Rangé Transboundary Air Pollution concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes. Geneva, 18 November 1991. (November).

United Nations. 1992. United Nations Framework Convention on Climate Change.

United Nations. 1994. Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Further Reduction of Sulphur Emissions. Oslo, 14 June 1994.

United Nations. 1998a. Kyoto Protocol to the United Nations Framework Convention on Climate Change.

United Nations. 1998b. Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Persistent Organic Pollutants. Aarhus, 24 June 1998.

United Nations. 1998c. Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Heavy Metals. Aarhus, 24 June 1998. (June).

United Nations. 1999. Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone. Gothenburg (Sweden), 30 November 1999. (November).

United Nations. 2010. The 1998 Protocol on Persistent Organic Pollutants, Including the Amendments Adopted by the Parties on 18 December 2009.

United Nations. 2013a. Protocol of the 1979 Convention on Long-Range Transboundary Air Pollution to

Abate Acidification, Eutrophicationand Ground-Level Ozone Gothenburg (Sweden), 30 November 1999. (February).

United Nations. 2013b. Protocol of the 1979 Convention on Long-Range Transboundary Air Pollution on Heavy Metals Aarhus, 24 June 1998. (October).

United Nations. 2015. Paris Agreement.

United Nations. 2017. The impact of population momentum on future population growth.

United Nations. 2018. The speed of urbanization around the world.

United Nations Environment Programme. 2000. The Montreal Protocol on Substances that Deplete the Ozone Layer.

United Nations Environment Programme. 2001. The Vienna Convention for the Protection of the Ozone Layer.

US EPA. 2012. The National Ambient Air Quality Standards for Particle Matter: Revised Air Quality Standards for Particle Pollution and Updates to the Air Quality Index (AQI) [WWW Document]. URL http://www.epa.gov/pm/2012/decfsstandards.pdf.

van der Kroon, B., Brouwer, R., & van Beukering, P.J.H. 2013. The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis. *Renewable and Sustainable Energy Reviews*. *Pergamon*. 20:504–513.

Vanker, A., Barnett, W., Nduru, P.M., Gie, R.P., Sly, P.D., & Zar, H.J. 2015. Home environment and indoor air pollution exposure in an African birth cohort study. *Science of The Total Environment*. *Elsevier*. 536:362–367.

Vedal, S. 1997. Ambient Particles and Health: Lines that Divide. *Journal of Air & Waste Management Association*. 47:551–581.

Viana, M., Kuhlbusch, T.A.J., Querol, X., Alastuey, A., Harrison, R.M., Hopke, P.K., Winiwarter, W., Vallius, M., Szidat, S., Prévôt, A.S.H., Hueglin, C., Bloemen, H., Wåhlin, P., Vecchi, R., Miranda, A.I., Kasper-Giebl, A., Maenhaut, W., & Hitzenberger, R. 2008. Source apportionment of particulate matter in Europe: A review of methods and results. *Journal of Aerosol Science*. *Pergamon*. 39(10):827–849.

Vijay Bhaskar, B. & Mehta, V.M. 2010. Atmospheric Particulate Pollutants and their Relationship with Meteorology in Ahmedabad. *Aerosol and Air Quality Research*. 10:301–315.

Wåhlin, P., Berkowicz, R., & Palmgren, F. 2006. Characterisation of traffic-generated particulate matter in Copenhagen. *Atmospheric Environment*. *Pergamon*. 40(12):2151–2159.

Wallace, L., Santa, C., & Calif, R. 2011. Validation of continuous particle monitors for personal , indoor , and outdoor exposures. *Journal of Exposure Science and Environmental Epidemiology*. *Nature Publishing Group*. 21(1):49–64.

Wang, G., Cheng, S., Wei, W., Wen, W., Wang, X., & Yao, S. 2015. Chemical Characteristics of Fine Particles Emitted from Different Chinese Cooking Styles. *Aerosol and Air Quality Research*. 15(6):2357–2366.

Ware, J.., Thibodeau, L.A., Speizer, F.E., Colome, S., & Ferris, B.. 1981. Assessment of the Health Effects of Atmospheric Sulfur Oxides and Particulate Matter: Evidence from Observational Studies. *Environmental Health Perspective1*. 41:255–276.

Watson, J.G. 1984. Overview of Receptor Model Principles. *Journal of the Air Pollution Control Association*. 34(6):619–623.

Watson, J.G., Chow, J.C., DuBois, D., Green, M., Frank, N., & Pitchford, M. 1997. Guidance for network design and optimum site exposure for PM2.5 and PM10. United States.

Watson, J.G., Chow, J.C., & Mathai, C. V. 1989. Receptor Models in Air Resources Management: A Summary of the APCA International Specialty Conference. *Journal of the Air Pollution Control Association*. 39(4):419–426.

Watson, J.G., Zhu, T., Chow, J.C., Engelbrecht, J., Fujita, E.M., & Wilson, W.E. 2002. Receptor modeling application framework for particle source apportionment. *Chemosphere*. *Pergamon*. 49(9):1093–1136.

Wernecke, B., Language, B., Piketh, S.J., & Burger, R.P. 2015a. Indoor and outdoor particulate matter concentrations on the Mpumalanga highveld-A case study. *Clean Air Journal*. 25(2):12–16.

Wernecke, B., Language, B., Piketh, S.J., & Burger, R.P. 2015b. Indoor and outdoor particulate matter concentrations on the Mpumalanga highveld-A case study. *The Clean Air Journal*. 25(2):12–16.

Wichmann, J. & Voyi, K. 2012. Ambient Air Pollution Exposure and Respiratory, Cardiovascular and Cerebrovascular Mortality in Cape Town, South Africa: 2001–2006. *Int. J. Environ. Res. Public Health*. 9:3978–4016.

Wichmann, J. & Voyi, K.V.V. 2005. Air Pollution Epidemiological Studies in South Africa: Need for Freshening Up. *Reviews on Environmental Health*. *De Gruyter*. 20(4):265–302.

Wichmann, J. & Voyi, K.V.V. 2006a. Impact of cooking and heating fuel use on acute respiratory health of preschool children in South Africa. *Southern African Journal of Epidemiology and Infection*. 21(2):48–54.

Wichmann, J. & Voyi, K.V. V. 2006b. Influence of Cooking and Heating Fuel Use on 1–59 Month Old Mortality in South Africa. *Maternal and Child Health Journal*. *Kluwer Academic Publishers-Plenum Publishers*. 10(6):553–561.

Wilson, W.E. & Suh, H.H. 2012. Fine particles and coarse particle: concentration relationship relevant to epidemiological studies. *Journal of the Air & Waste Management Association*. 47:1238–1249.

Wood, R., Racow, K., Bekker, L.-G., Morrow, C., Middelkoop, K., Mark, D., & Lawn, S.D. 2012. Indoor Social Networks in a South African Township: Potential Contribution of Location to Tuberculosis Transmission. *PLoS ONE*. *Public Library of Science*. 7(6):e39246.

World Health Organization. 1976. Selected methods of measuring air pollutants. World Health Organisation.

World Health Organization. 2000. Guidelines for Air Quality. Geneva.

World Health Organization. 2006a. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: Global update 2005.

World Health Organization. 2006b. Development of WHO Guidelines for Indoor Air Quality.

World Health Organization. 2009. WHO guidelines for indoor air quality: dampness and mould.

World Health Organization. 2010. WHO Guidelines for Indoor Air Quality: Selected Pollutants.

World Health Organization. 2014. WHO guidelines for indoor air quality: household fuel combustion.

Wright, C.Y., Oosthuizen, R., John, J., Garland, R.M., Albers, P., & Pauw, C. 2011. Air Quality and Human Health among a Low Income Community in the Highveld Priority Area. *Clean Air Journal2*. 20(1):15–20.

Wu, B., Shen, X., Cao, X., Yao, Z., & Wu, Y. 2016. Characterization of the chemical composition of PM2.5 emitted from on-road China III and China IV diesel trucks in Beijing, China. *Science of The Total Environment*. *Elsevier*. 551–552:579–589.

Yakovleva, E., Hopke, P.K., & Wallace, L.A. 1999. Receptor Modeling Assessment of Particle Total Exposure Assessment Methodology Data. *Environmental Science & Technology*. 33:3645–3652.

Yanosky, J.D., Williams, P.L., & MacIntosh, D.L. 2002. A comparison of two direct-reading aerosol monitors with the federal reference method for PM2.5in indoor air. *Atmospheric Environment*. 36(1):107–113.

Yassi, A. 2001. Basic Environmental Health. Oxford University Press.

Yatkin, S. & Bayram, A. 2008. Determination of major natural and anthropogenic source profiles for particulate matter and trace elements in Izmir, Turkey. *Chemosphere*. *Pergamon*. 71(4):685–696.

Yli-Tuomi, T., Lanki, T., Hoek, G., Brunekreef, B., & Pekkanen, J. 2008. Determination of the sources of Indoor PM 2.5 in Amsterdam and Helsinki. *Environmental Science & Technology*. 42:4440–4446.

Zhang, J., Chen, J., Yang, L., Sui, X., Yao, L., Zheng, L., Wen, L., Xu, C., & Wang, W. 2014. Indoor PM2.5 and its chemical composition during a heavy haze–fog episode at Jinan, China. *Atmospheric Environment*. *Pergamon*. 99:641–649.

Zhang, J. & Smith, K.R. 2003. Indoor air pollution: A global health concern. *British Medical Bulletin*. 68:209–225.

Zhang, J. & Smith, K.R. 2007. Household air pollution from coal and biomass fuels in China: Measurements, health impacts, and interventions. *Environmental Health Perspectives*. 115(6):848–855.

Zhang, Q., Shen, Z., Cao, J., Ho, K., Zhang, R., Bie, Z., Chang, H., & Liu, S. 2014. Chemical profiles of urban fugitive dust over Xi'an in the south margin of the Loess Plateau, China. *Atmospheric Pollution Research*. *Elsevier*. 5(3):421–430.

Zhang, R., Cao, J., Tang, Y., Arimoto, R., Shen, Z., Wu, F., Han, Y., Wang, G., Zhang, J., & Li, G. 2014. Elemental profiles and signatures of fugitive dusts from Chinese deserts. *Science of the Total Environment, The*. 472:1121–1129.

Zhang, Y. 2005. Indoor Air Quality Engineering. 1st ed. CRC Press: Boca Raton.

Zhang, Y., Cai, J., Wang, S., He, K., & Zheng, M. 2017. Review of receptor-based source apportionment research of fine particulate matter and its challenges in China. *Science of The Total Environment*. *Elsevier*. 586:917–929.

Zhao, W., Hopke, P.K., Gelfand, E.W., & Rabinovitch, N. 2007. Use of an expanded receptor model for personal exposure analysis in schoolchildren with asthma. *Atmospheric Environment*. *Pergamon*. 41(19):4084–4096.

Zhao, W., Hopke, P.K., Norris, G., Williams, R., & Paatero, P. 2006. Source apportionment and analysis

on ambient and personal exposure samples with a combined receptor model and an adaptive blank estimation strategy. *Atmospheric Environment*. *Pergamon*. 40(20):3788–3801.

Zhou, Z., Dionisio, K.L., Verissimo, T.G., Kerr, A.S., Coull, B., Howie, S., Arku, R.E., Koutrakis, P., Spengler, J.D., Fornace, K., Hughes, A.F., Vallarino, J., Agyei-Mensah, S., & Ezzati, M. 2014. Chemical Characterization and Source Apportionment of Household Fine Particulate Matter in Rural, Peri-urban, and Urban West Africa. *Environmental Science & Technology*. 48:1343–1351.

Zhu, C.-S., Cao, J.-J., Shen, Z.-X., Liu, S.-X., Zhang, T., Zhao, Z.-Z., Xu, H.-M., & Zhang, E.-K. 2012. Indoor and Outdoor Chemical Components of PM 2.5 in the Rural Areas of Northwestern China. *Aerosol and Air Quality Research*. 12:1157–1165.

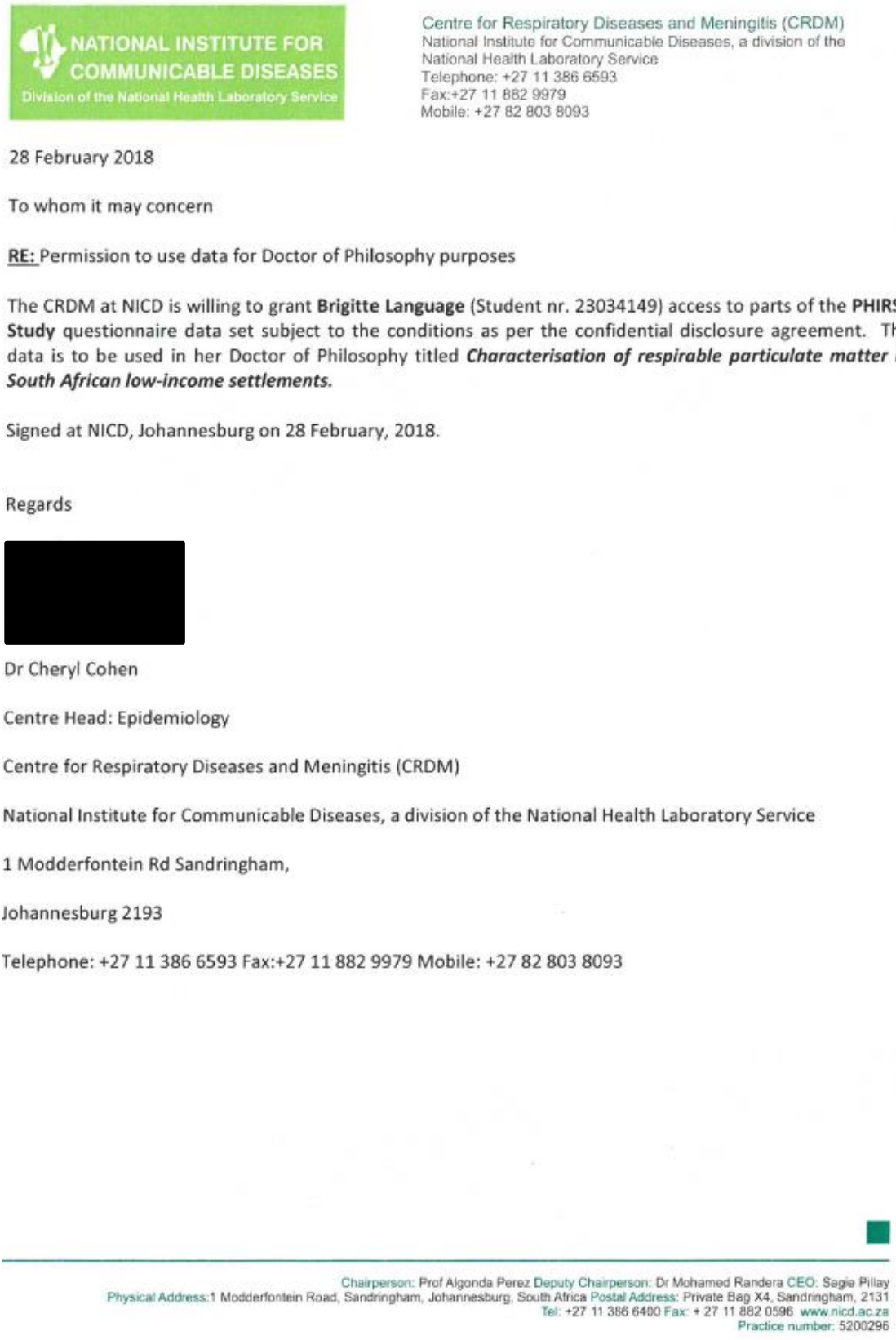
Zhu, K., Zhang, J., & Lioy, P.J. 2007. Evaluation and comparison of continuous fine particulate matter monitors for measurement of ambient aerosols. *Journal of the Air and Waste Management Association*. 57(12):1499–1506.

Zhu, Y., Smith, T.J., Davis, M.E., Levy, J.I., Robert Herrick, & Jiang, H. 2011. Comparing Gravimetric and Real-Time Sampling of PM2.5 Concentrations Inside Truck Cabins. *Journal of Occupational Environmental Hygiene*. 8(11):662–672.

APPENDICES

The appendices serve as supplementary materials and are referenced in the text where applicable.

Appendix A. Data use permission letters



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28 February 2018

To whom it may concern

RE: Permission to use data for Doctor of Philosophy purposes

The CRDM at NICD is willing to grant **Brigitte Language** (Student nr. 23034149) access to parts of the **PHIRST Study** questionnaire data set subject to the conditions as per the confidential disclosure agreement. The data is to be used in her Doctor of Philosophy titled ***Characterisation of respirable particulate matter in South African low-income settlements.***

Signed at NICD, Johannesburg on 28 February, 2018.

Regards

[redacted]

Dr Cheryl Cohen

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Figure A.1. Data use permission letter for the PHIRST project.

ENVIRONMENT &
HEALTH RESEARCH UNIT

DATE: 27 February 2018
TO: Brigitte Language
FROM: Dr Caradee Y Wright, Specialist Scientist, South African Medical Research Council
RE: Permission to use data for Doctor of Philosophy purposes
TITLE: Characterisation of respirable particulate matter in South African low-income settlements

To whom it may concern,

The South African Medical Research Council is willing to grant **Brigitte Language** (Student nr. 23034149) access to parts of the **iDEWS** questionnaire data set subject to the conditions as per the Environment and Health Research Unit confidential disclosure agreement. The data is to be used in her Doctor of Philosophy entitled '***Characterisation of respirable particulate matter in South African low-income settlements'.***

Signed at Pretoria on 27 February, 2018.

[redacted]

Name: Caradee Y Wright
Capacity: Specialist Scientist, iDEWS Project Primary Investigator
Organisation: South African Medical Research Council

Figure A.2. Data use permission letter for iDEWS project.

Appendix B. Climate Statistic (1980 - 2010) from South Africa Weather Service

Table B.1. Climate statistics for Bethal: No. 04788087

AIR TEMPERATURE IN DEGREES CELSIUS (Period: 1989 – 2010) (ϕ = 26°27' S; λ = 29°27' E), HT: 1650m

	Average of daily				Maximum												Minimum											
					Highest			Average number of days with maximum						Lowest			Highest			Average number of days with minimum						Lowest		
	Max	Min	Mean	Range	Max	yy/dd	Mean	>=35	>=30	>=25	>=20	>=15	<=10	Mean	yy/dd	Min	Max	yy/dd	Mean	>=20	<15	<10	<5	<0	<-5	Mean	yy/dd	Min
J	25.9	13.8	19.8	12.1	32.9	93/08	30.1	0.0	2.0	21.2	28.9	30.9	0.0	17.6	08/09	13.4	20.0	10/18	16.8	31.0	21.5	1.5	0.0	0.0	0.0	9.3	01/03	4.0
F	25.8	13.4	19.6	12.5	32.2	07/22	30.3	0.0	1.9	18.8	26.7	28.0	0.0	19.2	98/18	13.4	18.1	10/01	16.3	28.2	21.6	1.9	0.0	0.0	0.0	8.9	07/13	6.1
M	24.9	11.7	18.3	13.2	33.3	99/01	29.6	0.0	1.3	16.9	28.8	30.5	0.0	17.7	08/17	11.5	17.2	06/03	15.6	31.0	28.4	6.7	0.4	0.0	0.0	6.5	89/31	2.8
A	22.9	8.2	15.5	14.8	29.7	98/08	26.7	0.0	0.0	8.3	24.7	29.7	0.0	16.1	09/21	11.3	16.8	10/12	13.0	30.0	29.5	20.6	5.1	0.4	0.0	1.7	07/29	-2.6
M	20.5	3.3	11.9	17.2	27.4	98/01	24.5	0.0	0.0	1.3	19.5	29.3	0.2	13.7	97/28	7.7	13.0	10/01	10.0	31.0	31.0	30.0	20.8	4.8	0.3	-2.6	07/24	-7.0
J	18.3	0.4	9.4	17.9	26.1	10/06	22.8	0.0	0.0	0.4	9.4	26.1	0.4	11.6	94/29	6.4	9.8	06/13	7.5	30.0	30.0	30.0	26.4	14.8	1.0	-5.2	92/26	-8.8
J	18.3	-0.4	9.0	18.7	27.8	02/24	23.2	0.0	0.0	0.2	9.8	26.4	0.3	11.5	96/07	2.4	8.2	99/15	6.3	31.3	31.0	31.0	28.2	17.6	3.0	-6.4	92/03	-10.6
A	21.1	3.1	12.1	18.0	28.3	07/21	26.2	0.0	0.0	3.7	21.5	29.0	0.3	12.7	99/24	6.9	13.3	91/29	9.7	31.0	31.0	30.2	20.0	6.5	0.1	-4.0	03/21	-9.9
S	24.7	7.1	15.9	17.6	32.0	07/12	29.9	0.0	1.4	16.7	26.1	29.0	0.2	14.6	01/13	7.7	15.2	09/28	13.0	30.0	30.0	23.6	7.7	1.0	0.0	-0.2	89/07	-5.6
O	25.2	10.4	17.8	14.8	33.6	02/20	31.2	0.0	3.5	18.0	27.3	30.2	0.0	15.3	03/19	7.0	17.2	95/12	14.6	31.0	30.4	10.5	1.5	0.1	0.0	4.0	04/09	-2.0
N	25.2	12.0	18.6	13.2	34.1	05/03	31.0	0.0	2.3	17.5	26.8	29.2	0.0	16.1	98/07	8.3	17.3	97/08	15.6	29.9	27.5	5.3	0.2	0.0	0.0	6.3	92/14	1.0
D	25.9	13.3	19.6	12.6	33.3	06/14	30.4	0.0	1.7	19.3	28.4	29.5	0.0	18.8	94/11	12.3	18.3	08/30	16.5	29.5	23.3	1.5	0.1	0.0	0.0	8.2	89/01	1.7
YR	**23.2**	**8.0**	**15.6**	**15.2**	**34.1**	**05/03**	**32.2**	**0.0**	**14.0**	**142.0**	**278.0**	**348.0**	**2.0**	**8.7**	**96/07**	**2.4**	**20.0**	**10/18**	**17.2**	**364.0**	**335.0**	**193.0**	**111.0**	**45.0**	**4.0**	**-6.9**	**92/03**	**-10.6**

PRECIPITATION, DRY- AND WET BULB TEMPERATURES, RELATIVE HUMIDITY AND CLOUD COVER (Period: 1989 – 2010)

	Precipitation (mm)													P = 14 Years				Temperature (°C)						Relative Humidity (%)					Cloud (eighths)		
	Month	24 Hour		Total per month/year				Ave. no. of days with R (mm) >=										Mean on Hour			Mean on Hour											
	TOT	Max	yy/dd	Max	Year	Min	Year	0.1			1	5	10	30	Thund.	Hail	Snow	Fog	Dry Bulb			Wet Bulb			Mean on Hour			Mean		Mean on Hour		
								Ave.	Max	Min									8	14	20	8	14	20	8	14	20	Max	Min	8	14	20
J	147	91	06/07	375	2006	33	2001	13.0	21	7	11.6	7.9	4.9	1.2	6.8	0.7	-	-	17.0	24.5	19.5	15.4	18.4	16.4	83	52	71	96	27	4.6	5.6	4.9
F	100	75	96/11	273	1996	21	2007	10.0	20	2	8.4	5.1	3.4	0.7	4.4	0.6	-	-	16.1	24.6	19.2	14.9	18.2	16.2	87	52	72	97	27	4.7	5.5	4.5
M	86	97	00/30	176	2000	19	1989	9.7	19	5	7.9	4.6	2.4	0.6	4.5	0.7	-	-	14.3	23.8	17.7	13.3	17.0	14.7	89	48	70	98	25	4.5	5.3	3.7
A	37	47	10/05	105	2000	0	1991	5.9	12	0	4.6	2.3	1.3	0.1	1.7	1.0	-	-	10.7	22.1	15.0	9.7	14.8	11.8	89	41	67	98	22	3.5	4.5	2.5
M	17	38	97/25	84	1997	0	2007	2.7	8	0	2.2	1.2	0.6	0.1	0.6	1.0	-	-	5.6	19.9	11.0	4.6	11.9	7.9	86	34	61	98	17	2.4	2.7	1.4
J	11	40	89/04	62	1989	0	2005	1.9	7	0	1.4	0.8	0.3	0.0	0.3	0.9	-	-	2.3	17.8	8.5	1.4	9.9	5.4	83	30	57	98	12	2.1	1.7	0.9
J	3	19	96/07	30	2004	0	2008	0.8	3	0	0.5	0.2	0.1	0.0	0.1	1.1	-	-	1.6	17.7	8.7	0.6	9.4	4.9	82	28	52	98	10	2.0	1.5	0.9
A	11	34	09/01	55	2006	0	2008	1.6	6	0	1.2	0.5	0.3	0.0	0.5	0.7	-	-	5.5	20.4	11.9	4.1	11.3	7.4	79	27	48	98	9	2.1	1.9	1.2
S	17	56	93/30	85	1993	0	2008	2.8	11	0	1.9	0.9	0.6	0.0	1.6	0.4	-	-	11.0	23.8	15.7	8.6	13.9	10.6	72	29	49	98	10	2.3	2.8	1.8
O	86	96	07/08	311	2007	11	2006	10.1	19	0	8.5	4.7	3.0	0.3	3.4	0.3	-	-	14.5	24.0	16.9	12.1	15.6	13.0	74	39	62	96	13	3.9	5.0	4.0
N	115	83	97/12	230	1997	14	2002	11.8	18	0	10.0	6.1	3.9	0.6	12.1	0.0	-	-	16.2	23.9	17.7	13.9	16.8	14.3	75	47	68	96	22	4.5	5.6	4.9
D	133	55	90/06	254	1995	72	2004	14.9	21	7	12.6	8.4	5.0	0.5	13.7	0.0	-	-	17.1	24.5	18.9	15.1	18.1	15.8	79	51	71	97	27	4.6	5.5	5.0
YR	**751**	**97**	**00/30**	**1073**	**2000**	**393**	**1999**	**85.0**	**114**	**54**	**71.0**	**43.0**	**26.0**	**4.0**	**50**	**5**	**-**	**-**	**11.0**	**22.2**	**15.0**	**9.4**	**14.6**	**11.5**	**82**	**40**	**62**	**100**	**7**	**3.4**	**3.9**	**3.0**

Table B.2. Climate statistics for Klerksdorp: No. 04362041

AIR TEMPERATURE IN DEGREES CELSIUS (Period: 1992 – 2010) (ϕ = 26°53' S; λ = 26°37' E), HT: 1329m

	Average of daily				Maximum											Minimum										
	Max	Min	Mean	Range	Highest			Average number of days with maximum						Lowest			Highest			Average number of days with minimum						Lowest		
					Max	yy/dd	Mean	>=35	>=30	>=25	>=20	>=15	<=10	Mean	yy/dd	Min	Max	yy/dd	Mean	>=20	<15	<10	<5	<0	<-5	Mean	yy/dd	Min
J	28.7	16.1	22.4	12.6	42.6	07/23	33.7	0.6	11.5	24.3	28.4	28.8	0.0	20.9	00/15	16.9	24.5	07/23	19.5	0.4	7.5	0.2	0.0	0.0	0.0	12.1	02/11	7.9
F	28.5	15.6	22.1	13.0	36.5	07/22	32.5	0.2	9.1	20.2	23.8	24.4	0.0	22.0	06/06	15.2	20.5	98/06	18.2	0.1	8.6	0.2	0.0	0.0	0.0	12.3	00/01	9.2
M	27.0	13.6	20.3	13.3	36.8	99/02	30.9	0.2	5.2	19.0	24.4	25.9	0.0	19.7	08/17	13.7	20.5	07/02	16.9	0.1	17.3	2.4	0.2	0.0	0.0	9.6	02/03	4.3
A	24.9	9.8	17.4	15.1	31.7	98/02	28.6	0.0	0.6	15.6	25.8	28.3	0.0	18.2	93/12	17.0	17.2	99/10	14.8	0.0	27.6	13.4	2.5	0.1	0.0	3.3	02/01	-0.3
M	21.5	5.3	13.4	16.3	29.4	98/05	24.7	0.0	0.0	5.0	22.4	27.8	0.1	12.7	97/28	7.5	13.6	99/07	11.4	0.0	27.7	24.8	14.1	2.2	0.0	-1.4	07/24	-4.5
J	19.1	1.6	10.3	17.5	26.6	09/04	23.9	0.0	0.0	0.8	13.3	25.1	0.6	11.3	01/15	3.3	11.6	99/03	8.5	0.0	28.0	27.7	23.4	9.9	0.6	-3.8	01/06	-6.9
J	19.8	1.6	10.7	18.2	33.9	00/18	24.9	0.0	0.9	2.6	14.2	25.5	0.2	13.0	96/08	8.0	19.1	00/08	8.0	0.0	28.4	27.1	23.0	12.1	0.8	-3.4	96/07	-7.7
A	22.4	4.3	13.3	18.1	30.7	07/31	28.0	0.0	0.2	7.3	23.6	29.5	0.2	13.4	03/20	6.8	13.6	01/29	11.1	0.0	30.9	29.1	18.2	4.1	0.2	-2.6	10/01	-7.8
S	26.5	8.5	18.5	18.0	34.0	98/24	32.1	0.0	6.2	20.7	26.9	28.9	0.0	17.1	02/10	12.1	18.3	03/27	14.7	0.0	28.6	17.1	5.3	0.4	0.0	1.6	04/07	-2.2
O	27.9	12.6	20.2	15.3	38.1	06/24	33.5	0.3	10.4	22.7	27.6	28.5	0.1	18.6	03/19	8.6	19.5	08/15	17.2	0.0	22.6	5.7	0.5	0.0	0.0	6.0	96/17	1.0
N	28.5	13.9	21.2	14.6	35.7	99/03	33.9	0.3	10.9	22.3	26.3	26.9	0.0	20.8	09/20	13.4	22.3	97/09	18.5	0.2	16.4	2.2	0.2	0.0	0.0	8.0	02/01	4.3
D	29.2	15.4	22.3	13.8	38.1	06/15	33.2	0.9	12.3	25.3	27.7	27.9	0.0	21.9	05/21	14.5	21.7	06/16	18.8	0.5	11.4	0.7	0.1	0.0	0.0	10.2	02/03	4.1
YR	**25.1**	**9.6**	**17.4**	**15.6**	**42.6**	**07/23**	**35.7**	**3.0**	**67.0**	**183.0**	**280.0**	**323.0**	**1.0**	**9.4**	**01/15**	**3.3**	**24.5**	**07/23**	**20.5**	**1.0**	**254.0**	**151.0**	**88.0**	**29.0**	**1.6**	**-4.9**	**10/01**	**-7.8**

PRECIPITATION, DRY- AND WET BULB TEMPERATURES, RELATIVE HUMIDITY AND CLOUD COVER (Period: 1992 – 2010)

	Precipitation (mm)													P = 14 Years				Temperature (°C)						Relative Humidity (%)					Cloud (eighths)		
	Month	24 Hour		Total per month/year				Ave. no. of days with R (mm) >=										Mean on Hour			Mean on Hour			Mean on Hour			Mean		Mean on Hour		
	TOT	Max	yy/dd	Max	Year	Min	Year	0.1			1	5	10	30	Thund.	Hail	Snow	Fog	Dry Bulb			Wet Bulb			Mean on Hour			Max	Min			
								Ave.	Max	Min									8	14	20	8	14	20	8	14	20			8	14	20
J	88	71	09/28	183	2009	6	2001	11.5	18	5	8.4	5.4	3.3	0.4	-	-	-	-	20.2	27.0	21.5	16.6	18.1	16.6	77	51	68	90	18	-	-	-
F	58	46	98/17	174	2006	0	2001	7.5	17	0	4.8	3.2	2.0	0.4	-	-	-	-	19.4	26.9	21.2	15.7	17.8	16.1	77	48	67	94	26	-	-	-
M	67	51	99/13	125	2004	19	2009	9.7	17	1	6.7	3.6	2.1	0.4	-	-	-	-	17.1	25.5	19.1	13.6	16.6	14.4	81	49	70	95	26	-	-	-
A	26	89	93/02	83	2001	3	1994	6.6	17	1	3.7	1.4	0.9	0.1	-	-	-	-	13.4	23.9	16.3	11.4	14.6	12.1	82	42	66	98	21	-	-	-
M	15	31	01/01	54	2002	0	2007	3.8	11	0	1.9	1.1	0.6	0.1	-	-	-	-	8.2	21.0	12.4	6.7	11.7	8.3	81	35	59	95	20	-	-	-
J	4	12	09/07	23	2009	0	2007	1.4	9	0	0.8	0.3	0.1	0.0	-	-	-	-	4.0	18.7	9.8	2.6	9.3	5.4	79	31	53	97	13	-	-	-
J	3	10	97/27	37	2000	0	2005	1.2	9	0	0.6	0.3	0.0	0.0	-	-	-	-	4.4	19.0	10.7	0.8	8.2	4.2	74	30	47	97	11	-	-	-
A	7	16	02/17	34	2002	0	1999	2.1	8	0	1.0	0.5	0.3	0.0	-	-	-	-	7.9	21.5	13.3	4.6	10.4	6.5	65	26	41	96	8	-	-	-
S	13	39	07/26	93	2007	0	2004	2.6	18	0	1.4	0.4	0.3	0.1	-	-	-	-	13.7	25.6	17.6	8.1	12.4	8.8	56	24	37	96	7	-	-	-
O	31	38	98/08	102	2007	5	2002	7.6	18	2	5.2	1.9	1.3	0.1	-	-	-	-	17.8	26.7	19.9	12.6	14.8	12.5	63	34	50	98	11	-	-	-
N	65	98	06/13	159	1998	3	1997	8.9	19	3	6.1	3.3	1.8	0.5	-	-	-	-	19.5	26.9	20.7	14.3	16.0	13.8	66	40	55	99	13	-	-	-
D	87	52	01/24	173	2010	1	2000	12.2	107	1	8.5	5.2	3.2	0.4	-	-	-	-	20.4	27.6	21.4	15.9	17.2	15.5	71	43	62	98	17	-	-	-
YR	**459**	**98**	**06/13**	**765**	**1998**	**233**	**2002**	**75.1**	**107**	**48**	**49.0**	**27.0**	**16.0**	**2.0**	**-**	**-**	**-**	**-**	**13.7**	**24.1**	**16.9**	**10.3**	**13.9**	**11.2**	**72**	**38**	**56**	**99**	**7**	**-**	**-**	**-**

Table B.3. Climate statistics for Phalaborwa: No. 0681266D1

AIR TEMPERATURE IN DEGREES CELSIUS (Period: 1981 – 2010) (ϕ = 23°56' S; λ = 31°09' E), HT: 432m

	Average of daily				Maximum												Minimum											
					Highest			Average number of days with maximum						Lowest			Highest			Average number of days with minimum						Lowest		
	Max	Min	Mean	Range	Max	yy/dd	Mean	>=35	>=30	>=25	>=20	>=15	<=10	Mean	yy/dd	Min	Max	yy/dd	Mean	>=20	<15	<10	<5	<0	<-5	Mean	yy/dd	Min
J	32.0	20.8	26.4	11.2	41.5	83/11	38.3	6.4	21.9	28.9	30.1	30.2	0.0	23.3	00/17	19.6	26.4	09/09	23.8	20.4	0.0	0.0	0.0	0.0	0.0	17.2	94/07	14.9
F	31.7	20.7	26.2	11.0	42.4	10/13	37.4	4.6	19.6	26.7	27.5	27.6	0.0	25.1	01/28	19.1	26.2	03/05	23.6	18.7	0.1	0.0	0.0	0.0	0.0	17.0	08/11	14.7
M	30.9	19.8	25.4	11.1	41.0	90/03	36.8	4.2	17.8	27.0	28.6	28.8	0.0	23.7	04/13	17.8	25.2	98/11	22.9	13.9	0.4	0.0	0.0	0.0	0.0	16.0	85/29	12.4
A	29.0	16.7	22.9	12.3	39.8	98/05	35.6	1.4	10.9	25.3	28.9	29.2	0.0	22.3	10/25	17.8	23.1	04/05	20.8	2.9	7.7	0.4	0.0	0.0	0.0	11.4	07/30	5.8
M	27.3	12.7	20.0	14.6	39.1	98/08	34.0	0.6	6.8	23.4	29.5	30.1	0.1	20.3	97/29	15.2	21.2	98/10	18.5	0.2	23.2	6.1	0.7	0.0	0.0	7.4	07/23	1.6
J	25.5	9.5	17.5	16.0	34.3	09/04	31.3	0.0	2.9	15.1	27.2	28.6	0.5	19.5	84/14	14.0	17.9	88/08	15.4	0.0	26.3	17.1	1.6	0.0	0.0	5.2	94/30	0.6
J	24.9	8.9	16.9	16.0	35.3	02/30	30.6	0.0	2.2	13.8	28.0	29.5	0.7	17.9	96/17	11.9	18.0	88/08	15.3	0.0	28.6	18.3	2.7	0.0	0.0	4.6	96/03	2.5
A	26.6	10.7	18.7	15.9	37.1	09/31	33.1	0.4	6.5	20.2	29.1	30.7	0.3	18.5	96/20	13.1	19.9	95/06	16.8	0.0	27.4	11.4	1.1	0.0	0.0	5.8	94/24	2.6
S	28.8	14.1	21.5	14.7	40.7	08/08	37.9	3.5	13.1	23.2	28.1	29.6	0.0	18.8	84/14	14.0	25.0	99/26	19.0	0.4	16.8	2.5	0.0	0.0	0.0	8.9	94/11	4.5
O	29.6	16.8	23.2	12.8	44.1	10/11	38.5	5.5	14.6	23.7	29.1	30.2	0.0	19.0	88/13	15.5	24.8	02/29	21.3	2.8	7.4	0.2	0.0	0.0	0.0	12.0	87/05	7.4
N	30.5	18.6	24.6	11.9	41.5	08/03	38.7	5.8	17.3	25.1	28.9	29.5	0.0	20.7	98/08	16.4	25.6	06/03	22.7	9.4	2.7	0.0	0.0	0.0	0.0	13.7	06/07	9.0
D	31.6	19.9	25.8	11.7	42.1	88/23	38.7	7.0	19.6	28.0	30.1	30.2	0.0	22.8	88/08	19.7	26.0	97/17	23.7	15.2	0.7	0.0	0.0	0.0	0.0	15.4	94/13	10.8
YR	**29.0**	**15.8**	**22.4**	**13.2**	**44.1**	**10/11**	**40.6**	**38.0**	**148.0**	**271.0**	**333.0**	**342.0**	**2.0**	**16.4**	**96/17**	**11.9**	**26.4**	**09/09**	**24.8**	**81.0**	**136.0**	**54.0**	**6.0**	**0.0**	**0.0**	**4.1**	**94/30**	**0.6**

PRECIPITATION, DRY- AND WET BULB TEMPERATURES, RELATIVE HUMIDITY AND CLOUD COVER (Period: 1981 – 2010)

	Precipitation (mm)													P = 14 Years				Temperature (°C)						Relative Humidity (%)					Cloud (eighths)		
	Month	24 Hour		Total per month/year				Ave. no. of days with R (mm) >=										Mean on Hour			Mean on Hour										
	TOT	Max	yy/dd	Max	Year	Min	Year	0.1			1	5	10	30	Thund.	Hail	Snow	Fog	Dry Bulb			Wet Bulb			Mean on Hour			Mean		Mean on Hour		
								Ave.	Max	Min									8	14	20	8	14	20	8	14	20	Max	Min	8	14	20
J	70	66	81/21	246	1981	1	1989	7.6	16	2	5.8	3.1	2.3	0.8	-	-	-	-	24.0	30.60	26.30	21.20	22.70	21.60	80	54	69	96	30	5.0	4.2	2.1
F	75	115	00/24	338	2000	3	1998	8.0	24	2	5.7	3.0	2.2	0.8	-	-	-	-	23.5	30.30	25.80	21.00	22.30	21.10	82	53	68	96	31	4.8	4.3	1.9
M	53	80	04/23	137	2004	0	1982	7.3	16	1	5.1	2.8	1.6	0.4	-	-	-	-	22.7	29.80	24.70	20.30	21.70	20.50	82	51	70	96	31	4.0	3.5	1.5
A	22	47	99/22	86	2010	0	1987	4.4	11	0	3.0	1.1	0.6	0.2	-	-	-	-	20.3	28.10	21.60	17.90	19.90	18.10	83	50	72	96	26	3.7	3.3	1.4
M	8	25	96/16	49	1996	0	1986	2.4	9	0	1.3	0.4	0.3	0.0	-	-	-	-	17.1	26.60	17.90	14.60	17.90	14.90	82	44	72	97	20	2.0	2.0	0.7
J	5	22	85/23	25	1985	0	1981	1.6	8	0	0.8	0.3	0.2	0.0	-	-	-	-	13.9	24.70	15.30	11.40	15.60	12.20	80	40	70	96	15	1.6	1.9	0.7
J	6	36	84/11	85	1984	0	2010	1.7	6	0	1.0	0.3	0.1	0.0	-	-	-	-	13.4	24.20	15.40	11.30	15.50	12.20	82	41	68	97	15	2.0	1.7	0.7
A	5	27	87/25	34	1987	0	1993	1.7	10	0	1.1	0.3	0.1	0.0	-	-	-	-	16.0	25.80	17.70	12.80	16.40	13.50	76	40	63	97	12	2.3	2.0	0.9
S	9	30	07/29	48	1987	0	1995	2.3	8	0	1.3	0.4	0.3	0.0	-	-	-	-	19.3	27.90	21.00	15.50	18.20	15.70	72	42	59	96	13	2.8	2.4	1.2
O	27	82	89/22	104	1985	1	1995	5.2	11	1	3.4	1.7	0.8	0.1	-	-	-	-	21.1	28.60	23.20	17.40	19.50	17.70	74	47	62	96	19	4.3	3.5	2.1
N	64	58	96/26	146	1981	1	1995	8.4	15	3	6.0	3.6	2.2	0.5	-	-	-	-	22.5	29.30	24.40	18.90	20.90	19.50	76	51	67	97	23	5.1	3.9	2.5
D	75	100	90/05	189	1987	3	1997	8.4	14	0	6.0	3.4	2.1	1.0	-	-	-	-	23.7	30.30	25.60	20.40	22.10	20.90	78	52	67	96	25	5.1	4.5	2.6
YR	**406**	**115**	**00/24**	**763**	**2000**	**144**	**1994**	**57.0**	**88**	**30**	**39.0**	**20.0**	**12.0**	**4.0**	**-**	**-**	**-**	**-**	**19.8**	**28.00**	**21.60**	**16.90**	**19.40**	**17.30**	**79**	**47**	**67**	**99**	**9**	**3.5**	**3.1**	**1.5**

Table B.4. Climate statistics for Thohoyandou: No. 07236646

AIR TEMPERATURE IN DEGREES CELSIUS (Period: 1983 – 2010) (ϕ = 23°05' S; λ = 30°23' E), HT: 614m

	Average of daily				Maximum												Minimum											
					Highest			Average number of days with maximum						Lowest			Highest			Average number of days with minimum						Lowest		
	Max	Min	Mean	Range	Max	yy/dd	Mean	>=35	>=30	>=25	>=20	>=15	<=10	Mean	yy/dd	Min	Max	yy/dd	Mean	>=20	<15	<10	<5	<0	<-5	Mean	yy/dd	Min
J	30.1	19.6	24.9	10.5	39.7	83/11	36.4	2.8	17.0	27.5	30.4	30.8	0.0	21.6	10/05	15.5	24.9	05/06	22.9	14.4	0.9	0.0	0.3	0.0	0.0	15.7	10/01	12.5
F	29.8	19.6	24.7	10.2	42.6	92/26	35.7	2.1	13.9	25.6	27.9	28.0	0.0	23.0	01/28	17.8	26.6	92/27	22.6	12.7	0.5	0.0	0.0	0.0	0.0	15.9	90/28	12.9
M	28.9	18.5	23.7	10.4	38.4	83/03	35.0	1.5	11.9	26.9	30.4	31.0	0.0	21.4	04/13	16.8	24.1	92/01	21.8	8.0	1.9	0.0	0.0	0.0	0.0	14.4	85/01	11.5
A	27.4	15.8	21.6	11.6	37.7	98/08	33.9	0.5	7.9	22.6	29.1	30.0	0.0	20.2	10/24	15.4	21.5	99/21	19.8	1.2	10.9	0.6	0.0	0.0	0.0	11.1	90/01	7.4
M	25.9	12.3	19.1	13.6	37.1	87/13	32.5	0.2	4.4	18.6	29.4	30.9	0.0	18.4	97/29	11.3	20.0	83/21	17.2	0.0	26.3	6.4	0.3	0.0	0.0	7.6	07/24	2.7
J	23.8	9.9	16.9	13.9	33.0	90/22	30.2	0.0	1.5	11.4	25.6	29.9	0.0	16.8	84/14	12.4	18.5	89/26	14.9	0.0	29.3	16.3	1.1	0.0	0.0	5.8	85/16	2.0
J	23.4	9.5	16.5	13.9	34.3	02/30	30.0	0.0	0.9	10.7	25.4	30.2	1.0	15.9	96/17	9.3	15.9	89/18	14.1	0.0	30.5	18.1	1.6	0.0	0.0	5.1	96/02	1.8
A	25.5	11.2	18.4	14.3	37.0	08/29	33.6	0.3	5.4	17.0	27.1	30.0	0.0	17.2	87/14	12.5	20.1	94/14	16.3	0.0	27.8	10.3	0.3	0.0	0.0	6.4	00/19	3.8
S	27.8	14.1	21.0	13.7	39.8	08/24	36.9	2.8	12.1	21.2	26.9	29.3	0.0	16.9	84/14	12.4	24.3	94/18	19.3	0.2	19.1	1.7	0.0	0.0	0.0	9.2	93/18	6.0
O	28.4	16.3	22.4	12.1	41.6	10/11	37.6	4.0	13.1	22.3	28.4	30.7	0.0	17.3	03/19	12.7	26.3	92/25	21.1	2.2	9.8	0.4	0.0	0.0	0.0	11.1	96/01	6.8
N	29.1	17.8	23.5	11.3	41.0	08/03	37.4	3.9	14.8	22.9	27.8	29.9	0.0	17.8	98/07	10.4	25.8	04/21	22.6	6.5	4.6	0.1	0.0	0.0	0.0	13.0	02/27	8.3
D	29.8	19.2	24.5	10.6	41.2	89/20	36.8	3.2	16.1	26.1	30.0	30.4	0.0	20.5	09/14	17.1	26.4	92/04	22.8	12.1	1.4	0.1	0.0	0.0	0.0	14.6	00/25	6.0
YR	**27.5**	**15.3**	**21.4**	**12.2**	**42.6**	**92/26**	**39.3**	**21.0**	**119.0**	**253.0**	**338.0**	**361.0**	**1.0**	**14.0**	**96/17**	**9.3**	**26.6**	**92/27**	**24.0**	**57.0**	**163.0**	**54.0**	**3.0**	**0.0**	**0.0**	**4.4**	**96/02**	**1.8**

PRECIPITATION, DRY- AND WET BULB TEMPERATURES, RELATIVE HUMIDITY AND CLOUD COVER (Period: 1983 – 2010)

	Precipitation (mm)													P = 14 Years				Temperature (°C)						Relative Humidity (%)					Cloud (eighths)		
	Month	24 Hour		Total per month/year				Ave. no. of days with R (mm) >=										Mean on Hour			Mean on Hour										
	TOT	Max	yy/dd	Max	Year	Min	Year	0.1			1	5	10	30	Thund.	Hail	Snow	Fog	Dry Bulb			Wet Bulb			Mean on Hour			Mean		Mean on Hour		
								Ave.	Max	Min									8	14	20	8	14	20	8	14	20	Max	Min	8	14	20
J	126	118	91/28	420	1991	12	1989	12.4	24	7	8.5	5.1	3.4	1.1	2.9	0.4	0.0	1.1	22.1	28.3	24.9	20.0	21.7	20.9	81	57	70	97	28	5.8	4.9	3.7
F	146	199	00/23	1016	2000	5	2002	11.5	19	3	7.6	4.4	3.0	1.3	2.2	0.3	0.0	1.1	21.9	28.3	24.7	20.0	21.6	20.6	83	57	70	98	30	5.9	4.7	3.4
M	90	106	87/20	361	2004	6	1989	11.5	20	3	7.4	4.0	2.7	0.7	1.9	0.3	0.0	1.2	20.9	27.7	23.3	19.3	21.0	19.9	85	56	74	97	31	5.5	4.6	3.1
A	50	94	86/19	255	2010	0	1992	7.6	18	1	4.1	1.7	1.2	0.5	1.3	0.3	0.0	1.2	18.7	26.6	20.4	17.0	19.1	17.5	83	51	76	97	24	4.5	3.9	2.4
M	15	51	96/14	123	1996	0	1992	3.6	12	0	1.9	0.8	0.4	0.1	1.0	0.4	0.0	1.3	15.5	25.2	17.5	13.6	16.8	13.9	80	43	69	96	17	3.0	2.7	1.2
J	13	41	92/13	46	1992	0	1986	3.7	11	0	1.7	0.8	0.3	0.1	0.7	0.3	0.0	1.3	12.8	23.1	15.6	10.9	14.7	12.0	79	42	67	97	14	2.9	2.5	1.5
J	11	31	99/05	68	1984	0	1986	3.1	9	0	1.5	0.5	0.4	0.0	0.6	0.3	0.0	1.1	12.3	22.8	15.7	10.4	14.3	11.3	77	40	63	96	13	2.8	2.4	1.6
A	7	40	87/25	49	1987	0	1992	2.9	7	0	1.5	0.4	0.1	0.0	1.2	0.7	0.0	2.1	14.4	24.6	18.5	11.8	15.1	12.4	72	37	53	97	10	3.0	2.3	1.2
S	24	103	85/04	163	1985	0	1983	4.3	11	0	2.7	1.0	0.6	0.1	1.5	0.7	0.0	2.0	17.9	26.8	21.2	14.3	16.7	14.5	68	39	53	96	9	3.6	2.6	1.9
O	58	77	88/19	244	1988	1	2006	8.2	16	2	5.1	2.8	1.7	0.5	1.9	0.7	0.0	2.2	19.8	27.2	22.9	16.4	18.4	16.9	72	46	58	97	14	4.9	3.7	2.8
N	96	93	84/29	297	1984	7	1985	11.0	18	4	7.8	4.5	2.9	0.9	2.6	0.4	0.0	1.1	21.1	27.7	23.8	18.1	19.6	18.7	75	51	65	98	18	5.6	4.6	4.0
D	129	182	85/14	284	1985	31	1983	12.6	21	6	8.7	5.3	3.7	1.2	3.4	0.3	0.0	1.0	22.0	27.8	24.2	19.5	21.1	201.0	77	55	68	98	24	5.5	4.9	4.1
YR	**765**	**199**	**00/23**	**1654**	**2000**	**331**	**1983**	**92.2**	**121**	**63**	**58.0**	**31.0**	**20.0**	**7.0**	**21**	**5**	**0.0**	**17**	**18.3**	**26.4**	**21.0**	**15.9**	**18.4**	**16.6**	**78**	**48**	**65**	**99**	**7**	**4.4**	**3.6**	**2.6**

Appendix C. Gravimetric PM_4 and elemental mass concentrations

Table C.1. Mean (±SD) concentration, in $\mu g.m^{-3}$, of the residential indoor gravimetric PM_4 and associated trace elements measured between 2015 and 2017 categorised by community type, settlement, season, and household fuel use.

Settlement	Season	Fuel Use	N	Mean (±SD)																				
				PM_4	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Cu	Zn	Br	Sn	Ba	Pb	Det.
Coal-burning Communities																									
KwaDela	**Summer**	**ISFB**	144	103.75	0.58	0.42	0.03	0.37	0.01	0.85	4.51	0.62	2.34	0.66	1.39	1.25	1.34	1.67	4.93	4.03	0.14	2.83	39.57	6.98	39.57
				(187.55)	(0.37)	(0.10)	(0.02)	(0.15)	(0.01)	(0.40)	(1.07)	(0.24)	(0.63)	(0.17)	(0.34)	(0.31)	(0.34)	(0.45)	(1.22)	(1.03)	(0.11)	(1.95)		(1.75)	
KwaZamokuhle	**Summer**	**ISFB**	36	79.44	2.89	1.26	4.23	10.07	0.08	1.39	0.36	1.72	5.31	1.03	0.04	0.10	0.10	1.73	3.00	3.70	0.20	2.89	51.58	11.29	51.58
				(51.58)	(3.54)	(1.76)	(5.64)	(16.01)	(0.08)	(0.78)	(0.52)	(1.83)	(8.91)	(0.37)	(0.04)	(0.05)	(0.06)	(1.85)	(0.22)	(0.64)	(0.11)	(1.94)		(1.01)	
		NSFB	37	54.82	2.11	0.66	1.58	3.40	0.03	0.90	0.14	1.10	1.90	0.88	0.03	0.07	0.07	0.87	3.00	3.41	0.15	2.67	34.55	11.42	34.55
				(20.42)	(1.28)	(0.20)	(1.09)	(2.33)	(0.02)	(0.78)	(0.05)	(0.33)	(0.56)	(0.09)	(0.02)	(0.03)	(0.05)	(0.43)	(0.12)	(0.20)	(0.13)	(1.30)		(0.77)	
	Winter	**ISFB**	144	184.49	3.93	0.97	3.53	7.45	0.06	2.16	2.49	1.89	3.92	0.59	0.60	0.49	0.52	1.63	3.07	3.65	0.12	2.25	46.31	4.41	46.31
				(190.00)	(3.37)	(0.55)	(2.86)	(5.91)	(0.05)	(1.09)	(1.54)	(1.01)	(3.33)	(0.30)	(0.60)	(0.45)	(0.56)	(0.85)	(1.07)	(0.35)	(0.10)	(1.52)		(2.25)	
		NSFB	28	91.05	2.24	0.55	2.15	4.76	0.06	1.82	0.90	1.04	1.69	0.58	0.03	0.14	0.05	1.20	2.07	3.06	0.13	2.47	29.5	4.42	29.5
				(85.07)	(2.26)	(0.22)	(1.80)	(3.97)	(0.07)	(1.09)	(0.85)	(0.75)	(1.29)	(0.12)	(0.02)	(0.04)	(0.03)	(0.56)	(0.17)	(0.29)	(0.10)	(1.23)		(0.55)	
Summer			217	91.37	1.23	0.60	1.09	2.50	0.03	0.95	3.07	0.88	2.76	0.76	1.10	0.87	0.95	1.54	4.28	3.87	0.15	2.81	3.85	8.46	41.75
				(155.38)	(1.81)	(0.79)	(2.92)	(7.44)	(0.04)	(0.59)	(2.21)	(0.88)	(3.82)	(0.25)	(0.64)	(0.60)	(0.65)	(0.90)	(1.35)	(0.92)	(0.12)	(1.84)	(2.00)	(2.57)	
Winter			172	169.28	3.66	0.92	3.30	7.01	0.06	2.10	2.25	1.76	3.55	0.59	0.52	0.43	0.44	1.55	2.91	3.55	0.12	2.28	2.31	4.42	43.73
				(180.36)	(3.27)	(0.54)	(2.76)	(5.71)	(0.05)	(1.09)	(1.57)	(1.02)	(3.19)	(0.27)	(0.59)	(0.43)	(0.54)	(0.83)	(1.05)	(0.40)	(0.10)	(1.47)	(1.96)	(2.05)	
Coal-burning Community			389	125.82	2.30	0.72	2.12	4.49	0.04	1.46	2.71	1.27	3.11	0.69	0.86	0.67	0.74	1.55	3.67	3.73	0.14	2.58	3.32	6.78	42.95
				(171.11)	(2.83)	(0.72)	(3.05)	(7.09)	(0.05)	(1.02)	(2.00)	(1.04)	(3.57)	(0.27)	(0.68)	(0.57)	(0.65)	(0.87)	(1.40)	(0.75)	(0.11)	(1.70)	(2.11)	(3.09)	
Urbanised Community																									
Jouberton	**Summer**	**ISFB**	70	55.39	2.89	0.70	1.75	4.91	0.05	1.20	1.30	0.78	2.08	0.17	0.28	0.25	0.23	1.12	1.31	1.50	0.05	1.05	1.13	1.53	24.28
				(65.47)	(1.98)	(0.46)	(1.13)	(3.05)	(0.03)	(0.83)	(0.93)	(0.37)	(1.74)	(0.14)	(0.25)	(0.20)	(0.24)	(0.58)	(0.45)	(0.28)	(0.05)	(0.66)	(0.80)	(1.25)	
		NSFB	500	77.67	3.78	0.96	2.28	6.14	0.05	1.34	1.47	0.95	2.27	0.23	0.36	0.31	0.30	1.39	1.43	1.51	0.06	1.00	1.35	1.81	28.99
				(193.19)	(4.02)	(1.05)	(2.54)	(6.31)	(0.05)	(1.18)	(0.98)	(0.83)	(2.33)	(0.20)	(0.30)	(0.26)	(0.29)	(1.22)	(0.78)	(0.61)	(0.04)	(0.79)	(0.93)	(1.51)	
	Winter	**ISFB**	59	96.97	2.78	0.75	2.39	7.01	0.05	0.86	1.25	1.17	1.01	0.17	0.02	0.11	0.06	1.98	1.02	1.58	0.07	0.99	0.05	0.07	23.39
				(91.13)	(1.99)	(0.46)	(2.13)	(6.04)	(0.06)	(0.80)	(1.55)	(1.83)	(0.94)	(0.13)	(0.01)	(0.10)	(0.04)	(1.48)	(0.18)	(0.30)	(0.05)	(0.68)	(0.05)	(0.09)	
		NSFB	527	72.71	3.08	1.17	2.46	7.34	0.05	0.71	0.90	0.87	1.51	0.16	0.02	0.15	0.05	1.93	1.03	1.54	0.08	1.07	0.04	0.05	24.21
				(68.49)	(2.90)	(1.24)	(2.56)	(7.58)	(0.07)	(0.64)	(0.90)	(1.25)	(2.51)	(0.12)	(0.01)	(0.27)	(0.04)	(1.49)	(0.60)	(0.81)	(0.19)	(1.21)	(0.05)	(0.04)	
Summer			570	74.93	3.68	0.93	2.22	5.99	0.05	1.32	1.45	0.93	2.25	0.23	0.35	0.30	0.30	1.36	1.42	1.51	0.06	1.01	1.32	1.78	28.46
				(182.49)	(3.84)	(1.00)	(2.41)	(6.02)	(0.05)	(1.14)	(0.97)	(0.79)	(2.27)	(0.20)	(0.29)	(0.26)	(0.29)	(1.16)	(0.74)	(0.58)	(0.05)	(0.78)	(0.92)	(1.49)	
Winter			586	75.15	3.05	1.13	2.46	7.31	0.05	0.73	0.93	0.90	1.46	0.16	0.02	0.14	0.06	1.93	1.03	1.54	0.08	1.06	0.04	0.05	24.13
				(71.38)	(2.82)	(1.20)	(2.52)	(7.43)	(0.07)	(0.66)	(0.98)	(1.32)	(2.41)	(0.12)	(0.01)	(0.26)	(0.04)	(1.49)	(0.57)	(0.77)	(0.18)	(1.17)	(0.05)	(0.05)	
Urban Community			1156	75.04	3.38	1.00	2.34	6.65	0.05	1.02	1.21	0.91	1.86	0.19	0.20	0.22	0.18	1.65	1.22	1.53	0.07	1.03	0.93	1.05	26.69
				(137.79)	(3.40)	(1.07)	(2.47)	(6.80)	(0.06)	(0.98)	(1.01)	(1.08)	(2.37)	(0.17)	(0.27)	(0.27)	(0.24)	(1.37)	(0.69)	(0.69)	(0.13)	(1.00)	(0.96)	(1.41)	

Table C.1 (Continuous)

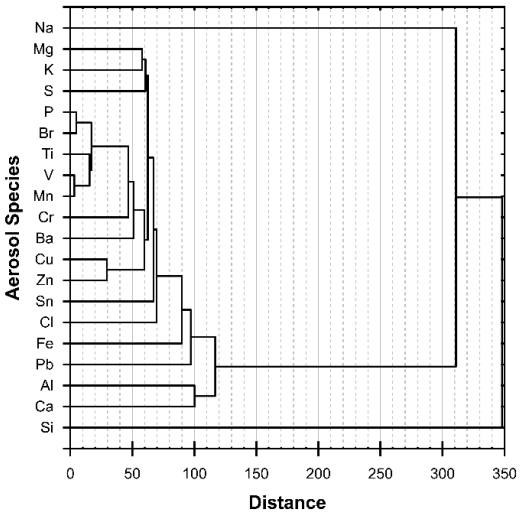
Settlement	Season	Fuel Use	N	Mean (±SD)																				
				PM4	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Cu	Zn	Br	Sn	Ba	Pb	Det.
Wood-burning Communities																									
Agincourt	**Summer**	**ISFB**	96	89.98	4.76	0.96	1.76	5.51	0.04	0.79	1.62	1.09	2.66	0.15	0.02	0.13	0.03	0.65	1.00	1.45	0.06	1.02	0.05	0.79	24.54
				(111.54)	(3.99)	(0.95)	(1.64)	(5.13)	(0.05)	(0.78)	(1.24)	(1.33)	(2.51)	(0.11)	(0.01)	(0.19)	(0.02)	(0.57)	(0.15)	(0.22)	(0.04)	(0.76)	(0.04)	(1.13)	
		NSFB	66	72.33	5.65	1.12	2.03	6.56	0.04	0.62	1.61	1.00	1.68	0.11	0.02	0.10	0.03	0.59	1.03	1.47	0.06	0.94	0.05	0.06	24.77
				(33.84)	(4.37)	(0.65)	(1.90)	(6.34)	(0.03)	(0.59)	(1.16)	(0.91)	(1.34)	(0.11)	(0.01)	(0.15)	(0.03)	(0.51)	(0.08)	(0.12)	(0.04)	(0.58)	(0.04)	(0.04)	
		OSFB	440	70.31	5.32	0.98	1.67	5.29	0.03	0.60	1.69	0.94	1.79	0.11	0.02	0.10	0.03	0.55	1.01	1.44	0.05	0.97	0.05	0.31	22.95
				(77.92)	(4.91)	(0.98)	(2.03)	(6.46)	(0.03)	(0.60)	(1.55)	(1.01)	(2.58)	(0.11)	(0.01)	(0.16)	(0.03)	(0.51)	(0.28)	(0.40)	(0.04)	(0.60)	(0.05)	(0.77)	
	Winter	**ISFB**	94	95.23	11.64	2.34	3.84	12.61	0.06	1.20	2.12	1.87	3.66	0.31	0.29	0.56	0.30	1.76	1.37	1.48	0.05	0.97	1.13	1.65	49.21
				(94.76)	(6.84)	(2.99)	(2.40)	(7.64)	(0.04)	(0.86)	(1.20)	(0.99)	(2.78)	(0.18)	(0.25)	(1.93)	(0.28)	(3.87)	(0.41)	(0.17)	(0.03)	(0.65)	(0.44)	(1.28)	
		NSFB	60	82.05	11.54	2.31	3.87	12.94	0.06	1.09	2.19	2.01	2.85	0.30	0.32	0.48	0.30	1.56	1.41	1.49	0.06	1.06	1.05	1.82	48.71
				(71.91)	(8.16)	(2.21)	(2.50)	(7.79)	(0.04)	(0.77)	(1.54)	(1.07)	(1.63)	(0.18)	(0.25)	(1.42)	(0.28)	(2.77)	(0.46)	(0.15)	(0.04)	(0.72)	(0.52)	(1.27)	
		OSFB	455	83.88	11.80	1.98	3.47	11.73	0.06	1.21	2.13	1.76	3.33	0.25	0.23	0.40	0.22	1.39	1.28	1.50	0.06	1.04	1.02	1.33	46.19
				(89.89)	(7.51)	(1.49)	(2.64)	(8.58)	(0.04)	(0.87)	(1.33)	(1.03)	(3.04)	(0.20)	(0.27)	(1.41)	(0.27)	(2.69)	(0.50)	(0.34)	(0.04)	(0.63)	(0.64)	(1.46)	
Giyani	**Spring**	**ISFB**	3	130.66	5.18	3.42	2.15	7.39	0.08	1.06	1.06	2.70	2.08	0.34	0.01	0.07	0.03	1.72	1.08	1.65	0.02	1.20	-	2.64	33.88
				(27.48)	(0.74)	(0.39)	(0.09)	(0.57)	(0.01)	(0.15)	(0.09)	(0.71)	(0.38)	(0.02)	-	(0.02)	(0.01)	(0.15)	(0.05)	(0.13)	(0.02)	(1.15)	-	(0.06)	
		NSFB	3	102.70	5.31	5.01	2.99	10.54	0.12	1.11	1.07	2.92	3.07	0.36	0.02	0.10	0.06	2.87	1.06	1.58	0.03	1.54	-	2.48	42.24
				(53.06)	(0.56)	(2.26)	(0.91)	(3.48)	(0.05)	(0.19)	(0.13)	(0.83)	(1.12)	(0.07)	(0.01)	(0.02)	(0.03)	(1.04)	(0.03)	(0.09)	(0.01)	(0.83)	-	(0.15)	
		OSFB	3	173.64	6.43	8.06	5.20	18.43	0.20	1.17	1.28	3.53	3.58	0.46	0.03	0.13	0.10	4.80	1.08	1.43	0.07	0.71	-	2.58	59.27
				(10.34)	(0.58)	(1.38)	(0.94)	(3.53)	(0.03)	(0.24)	(0.16)	(0.60)	(0.28)	(0.04)	(0.00)	(0.01)	(0.02)	(1.10)	(0.03)	(0.03)	(0.07)	-	-	(0.10)	
	Summer	**NSFB**	7	82.76	4.78	1.26	0.55	2.02	0.02	0.53	1.78	0.56	1.28	0.25	0.02	0.06	0.03	0.55	1.01	1.43	0.05	0.87	0.08	2.42	19.55
				(23.36)	(2.05)	(0.34)	(0.20)	(0.69)	(0.01)	(0.11)	(0.60)	(0.10)	(0.45)	(0.05)	(0.01)	(0.03)	(0.02)	(0.18)	(0.27)	(0.36)	(0.03)	(0.61)	(0.01)	(0.60)	
		OSFB	45	117.80	2.78	0.62	0.55	1.77	0.03	0.44	1.40	0.60	1.20	0.26	0.02	1.81	0.03	3.72	1.03	1.48	0.04	1.16	0.06	2.36	21.36
				(180.38)	(2.42)	(0.56)	(0.66)	(2.06)	(0.02)	(0.32)	(0.78)	(0.29)	(0.80)	(0.07)	(0.01)	(4.09)	(0.01)	(7.72)	(0.27)	(0.38)	(0.02)	(0.72)	(0.04)	(0.80)	
	Winter	**NSFB**	6	17.51	2.64	1.82	0.91	3.30	0.03	0.56	0.88	0.83	2.08	0.28	0.02	0.08	0.03	0.90	1.14	1.65	0.04	0.85	0.05	2.57	20.66
				(10.18)	(1.86)	(1.36)	(0.69)	(2.53)	(0.02)	(0.57)	(0.38)	(0.40)	(0.54)	(0.07)	(0.02)	(0.02)	(0.02)	(0.61)	(0.29)	(0.36)	(0.03)	(0.78)	(0.03)	(0.70)	
		OSFB	43	54.75	7.64	2.13	3.82	11.44	0.09	1.42	1.80	1.95	3.18	0.38	0.02	0.08	0.04	1.71	1.04	1.51	0.04	1.18	0.06	2.40	41.93
				(83.70)	(3.54)	(0.84)	(2.83)	(7.56)	(0.06)	(0.69)	(1.10)	(0.79)	(2.14)	(0.11)	(0.02)	(0.03)	(0.02)	(1.02)	(0.13)	(0.17)	(0.04)	(0.76)	(0.06)	(0.36)	
Spring			9	135.67	5.64	5.50	3.45	12.12	0.13	1.11	1.13	3.05	2.91	0.38	0.02	0.10	0.06	3.13	1.07	1.55	0.04	1.28	-	2.57	45.24
				(43.32)	(0.81)	(2.44)	(1.51)	(5.52)	(0.06)	(0.18)	(0.16)	(0.73)	(0.90)	(0.07)	(0.01)	(0.03)	(0.03)	(1.55)	(0.03)	(0.12)	(0.04)	(0.87)	-	(0.12)	
Summer			654	76.80	5.09	0.96	1.63	5.18	0.03	0.62	1.65	0.94	1.86	0.13	0.02	0.22	0.03	0.78	1.01	1.45	0.05	0.99	0.05	0.65	23.34
				(91.51)	(4.61)	(0.92)	(1.92)	(6.11)	(0.04)	(0.62)	(1.42)	(1.02)	(2.40)	(0.12)	(0.01)	(1.15)	(0.03)	(2.20)	(0.25)	(0.36)	(0.04)	(0.63)	(0.05)	(1.08)	
Winter			658	82.83	11.39	2.07	3.56	11.87	0.06	1.20	2.10	1.81	3.31	0.27	0.23	0.40	0.22	1.48	1.29	1.50	0.06	1.04	1.00	1.55	46.41
				(88.78)	(7.36)	(1.82)	(2.61)	(8.32)	(0.04)	(0.85)	(1.32)	(1.02)	(2.84)	(0.19)	(0.26)	(1.45)	(0.27)	(2.81)	(0.47)	(0.30)	(0.04)	(0.65)	(0.62)	(1.38)	
Wood-burning Community			1321	80.20	8.28	1.60	2.61	8.57	0.05	0.92	1.87	1.39	2.59	0.20	0.14	0.31	0.13	1.15	1.15	1.48	0.05	1.01	0.62	1.15	35.27
				(90.04)	(6.90)	(1.63)	(2.48)	(8.02)	(0.04)	(0.80)	(1.39)	(1.11)	(2.72)	(0.18)	(0.22)	(1.31)	(0.22)	(2.54)	(0.40)	(0.33)	(0.04)	(0.65)	(0.67)	(1.33)	
Residential Indoor Mean			2866	84.31	5.53	1.26	2.43	7.24	0.05	1.03	1.73	1.19	2.38	0.26	0.28	0.32	0.23	1.40	1.52	1.80	0.07	1.24	1.31	2.18	33.45
				(125.02)	(5.90)	(1.39)	(2.56)	(7.55)	(0.05)	(0.92)	(1.45)	(1.11)	(2.76)	(0.25)	(0.43)	(0.94)	(0.38)	(1.97)	(1.12)	(0.95)	(0.10)	(1.13)	(1.60)	(2.88)	

Appendix D. Source Apportionment Results

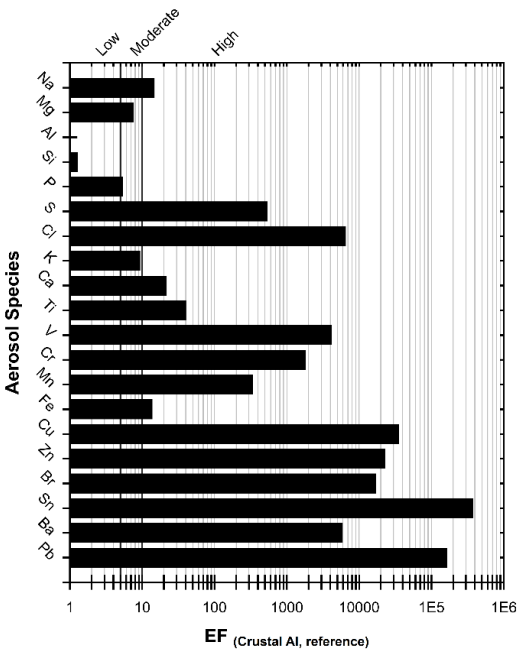
A **PCA (Varimax Rotated)**

Receptor	Residential Indoor			
Source	Solid Fuel Comb.	Crustal Soil	Traffic	Waste Burning
	F1	F2	F3	F4
Na	0.21	**0.67**	-0.07	-0.44
Mg	0.10	**0.79**	-0.03	-0.18
Al	-0.06	**0.93**	0.12	0.09
Si	-0.08	**0.94**	0.08	-0.01
P	-0.07	**0.87**	0.06	0.12
S	-0.04	0.48	0.04	0.30
Cl	**0.80**	0.35	-0.05	-0.19
K	0.08	**0.89**	0.02	0.05
Ca	0.13	**0.82**	0.05	0.14
Ti	**0.53**	0.44	0.15	**0.58**
V	**0.93**	-0.05	0.12	0.20
Cr	0.27	-0.06	**0.92**	-0.03
Mn	**0.92**	0.01	0.19	0.20
Fe	0.04	0.26	**0.94**	0.05
Cu	**0.81**	-0.05	0.05	**0.54**
Zn	**0.56**	0.02	0.01	**0.70**
Br	0.04	0.04	0.02	0.28
Sn	0.17	-0.03	-0.06	**0.64**
Ba	**0.93**	-0.08	0.11	0.22
Pb	**0.61**	0.01	0.05	**0.63**
Expl.Var	5.05	5.70	1.88	2.53
Prp.Totl	0.25	0.29	0.09	0.13
Eigenvalue	6.71	5.29	1.72	1.44
Variability %	33.57	26.43	8.59	7.22
Cumulative %	33.57	60.00	68.59	75.81

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

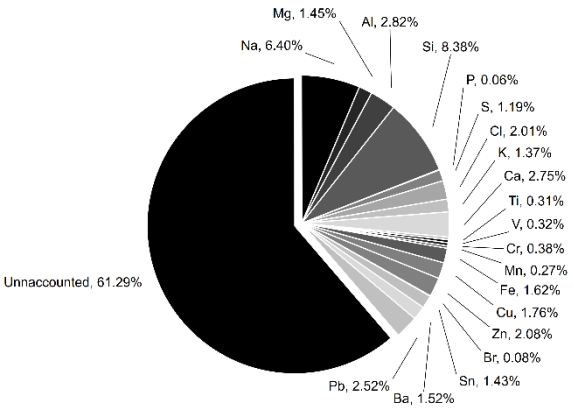
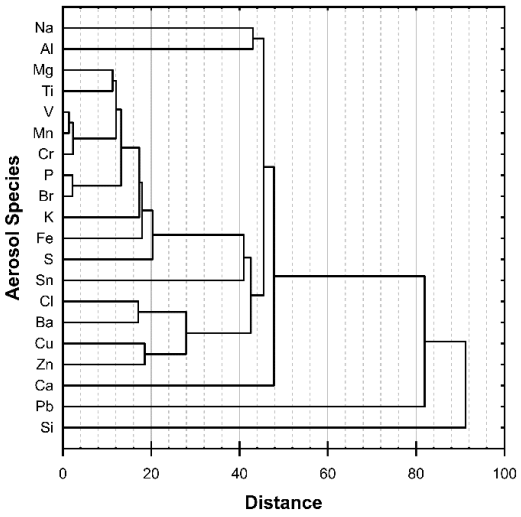


Figure D.1. The source characterisation results for the residential indoor environment of low-income settlements in South Africa (N=2866) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

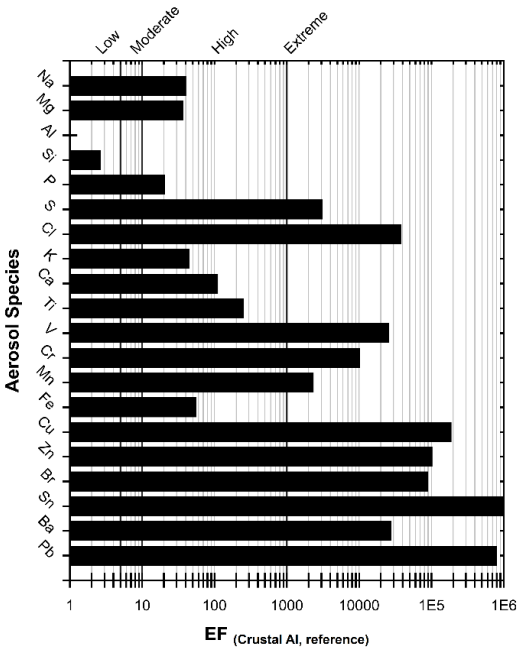
A **PCA (Varimax Rotated)**

Receptor	C		
Source	Crustal Soil	Road Traffic	Solid Fuel Comb.
	F1	F2	F3
Na	**0.79**	0.00	-0.09
Mg	**0.91**	0.04	0.21
Al	**0.95**	-0.25	0.02
Si	**0.96**	-0.22	0.04
P	**0.89**	-0.24	0.03
S	**0.57**	-0.28	-0.37
Cl	0.01	**0.98**	-0.11
K	**0.90**	-0.08	-0.05
Ca	**0.86**	0.04	0.13
Ti	**0.56**	0.17	**0.74**
V	-0.13	**0.98**	0.06
Cr	-0.12	**0.98**	0.04
Mn	-0.11	**0.98**	0.08
Fe	**0.79**	0.45	0.18
Cu	-0.12	**0.93**	0.29
Zn	0.12	**0.67**	0.33
Br	0.01	0.00	0.41
Sn	-0.03	0.06	0.39
Ba	-0.14	**0.98**	0.07
Pb	0.05	0.14	**0.91**
Expl.Var	0.35	0.33	0.11
Prp.Totl	7.71	6.29	1.79
Eigenvalue	7.71	6.29	1.79
Variability %	38.57	31.43	8.93
Cumulative %	38.57	70.01	78.94

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

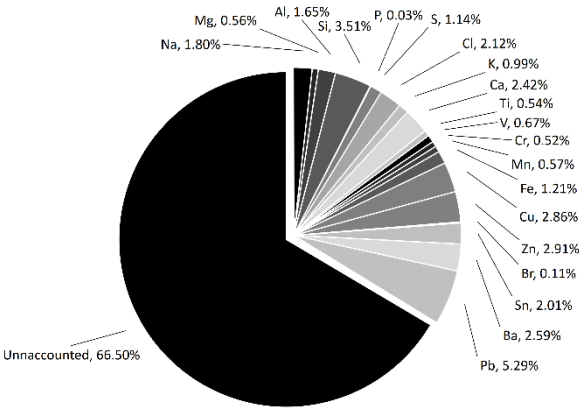
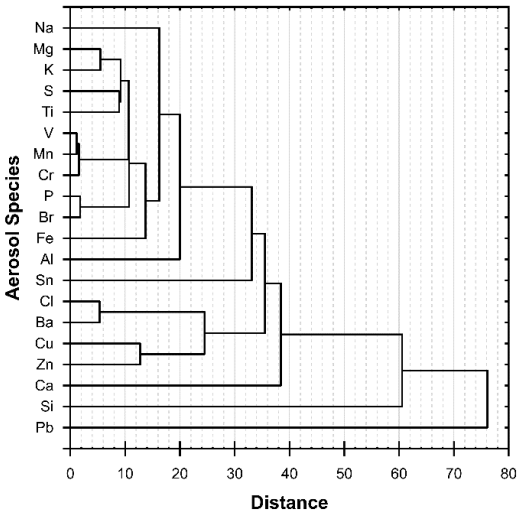


Figure D.2. The source characterisation results for the residential indoor environment of coal-burning communities in South Africa (N=389) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

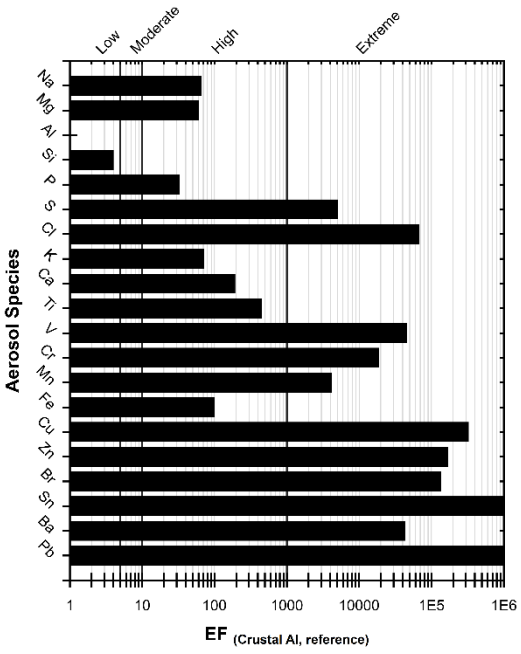
A **PCA (Varimax Rotated)**

Receptor	C-S		
Source	Crustal Soil	Road Traffic	Waste Burning
	F1	F2	F3
Na	**0.89**	-0.26	0.13
Mg	**0.98**	-0.06	0.08
Al	**0.95**	-0.26	0.09
Si	**0.98**	-0.18	0.04
P	**0.93**	-0.23	0.16
S	0.36	-0.18	0.03
Cl	-0.10	**0.99**	-0.07
K	**0.95**	-0.14	0.18
Ca	**0.96**	0.10	0.01
Ti	**0.75**	-0.09	**0.61**
V	-0.18	**0.98**	-0.06
Cr	-0.18	**0.98**	-0.05
Mn	-0.16	**0.98**	-0.04
Fe	**0.83**	0.52	0.13
Cu	-0.09	**0.93**	0.33
Zn	0.14	**0.67**	**0.67**
Br	0.11	0.03	0.40
Sn	-0.04	0.07	**0.57**
Ba	-0.19	**0.98**	-0.05
Pb	0.25	-0.40	**0.82**
Expl.Var	7.93	6.86	2.22
Prp.Totl	0.40	0.34	0.11
Eigenvalue	9.25	5.99	1.77
Variability %	46.27	29.94	8.83
Cumulative %	46.27	76.20	85.04

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

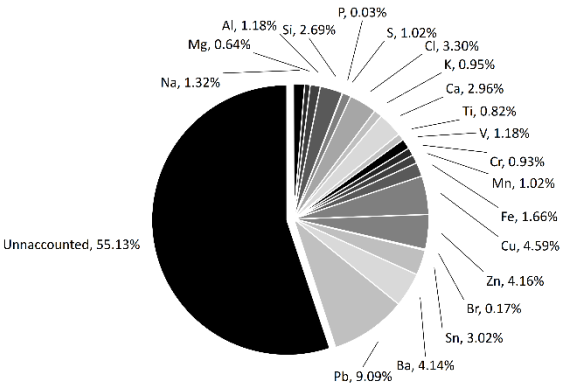
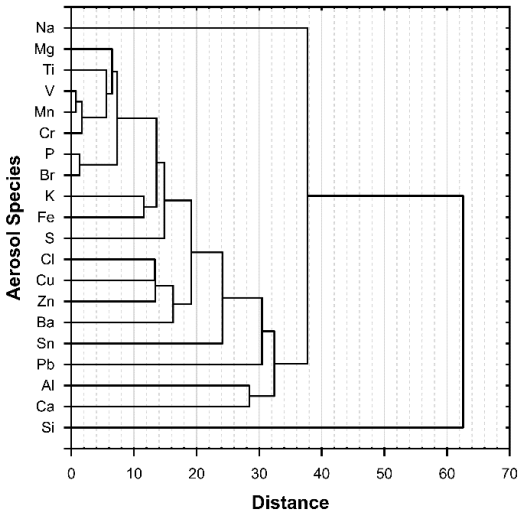


Figure D.3. The summer source characterisation results for the residential indoor environment of coal-burning communities in South Africa (N=217) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

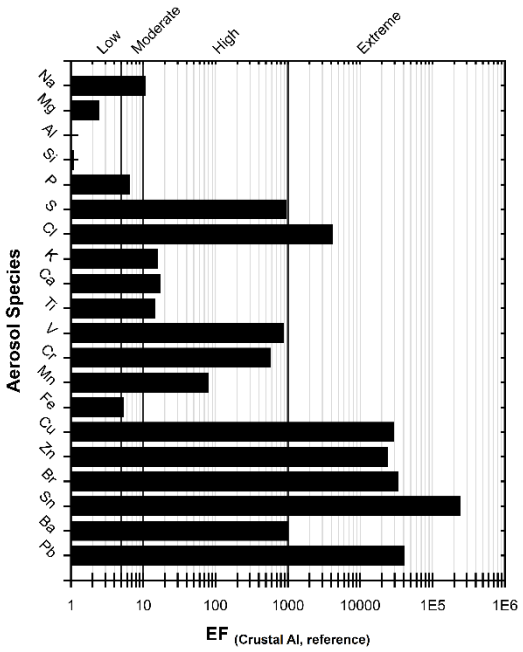
A **PCA (Varimax Rotated)**

Receptor	C-W			
Source	Solid Fuel Comb.	Crustal Soil	Road Traffic	Waste Burning
	F1	F2	F3	F4
Na	0.53	**0.59**	0.13	0.01
Mg	0.37	**0.83**	0.07	-0.06
Al	-0.04	**0.96**	0.14	0.05
Si	-0.05	**0.97**	0.12	0.02
P	-0.07	**0.86**	0.01	-0.18
S	-0.27	**0.70**	-0.02	0.21
Cl	**0.94**	0.19	-0.11	-0.03
K	0.31	**0.80**	-0.18	-0.09
Ca	0.05	**0.78**	0.06	0.07
Ti	0.28	**0.65**	**0.66**	0.02
V	**0.98**	0.04	0.18	0.01
Cr	**0.97**	0.05	0.17	0.02
Mn	**0.97**	0.05	0.19	0.01
Fe	0.37	**0.73**	0.38	0.09
Cu	**0.99**	-0.03	-0.04	0.01
Zn	**0.66**	0.13	**-0.51**	0.06
Br	-0.05	-0.10	0.30	**-0.72**
Sn	0.01	0.06	-0.22	**-0.70**
Ba	**0.98**	0.02	0.18	0.01
Pb	**0.53**	0.33	**0.72**	-0.02
Expl.Var	7.22	6.51	1.71	1.13
Prp.Totl	0.36	0.33	0.09	0.06
Eigenvalue	8.78	5.26	1.41	1.12
Var. %	43.91	26.31	7.04	5.58
Cum. %	43.91	70.22	77.26	82.84

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal A)**



D **Elemental Abundance (%)**

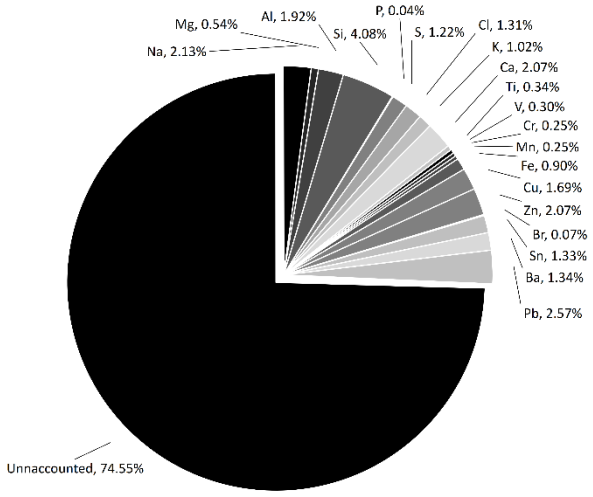
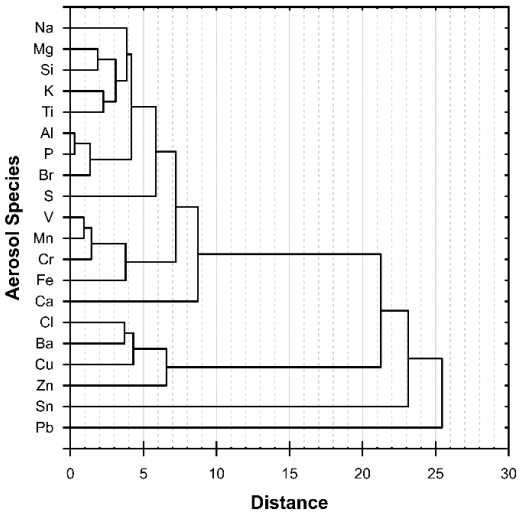


Figure D.4. The winter source characterisation results for the residential indoor environment of coal-burning communities in South Africa (N=389) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

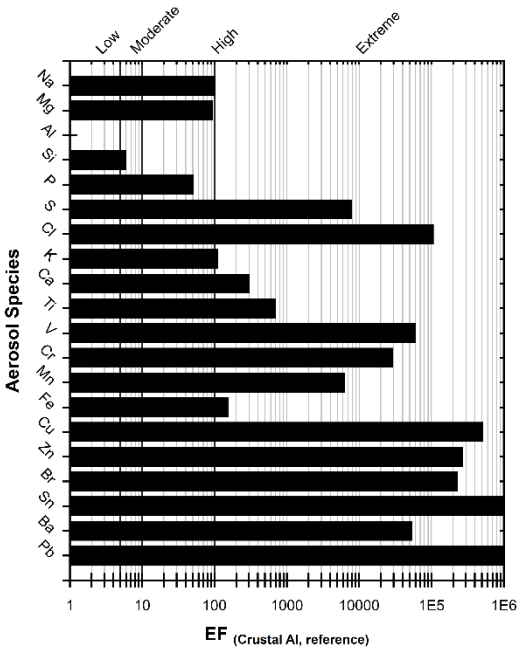
A **PCA (Varimax Rotated)**

Receptor	C-KD-S-ISFB		
Source	Solid Fuel Comb.	Crustal Soil	Biomass Burning
	F1	F2	F3
Na	0.15	**0.65**	0.23
Mg	**0.93**	0.17	0.16
Al	0.23	**0.68**	-0.18
Si	0.27	**0.69**	0.01
P	**0.56**	0.35	0.29
S	-0.16	**0.69**	0.00
Cl	**0.95**	0.15	0.21
K	**0.55**	0.37	**0.54**
Ca	**0.92**	0.12	0.15
Ti	**0.96**	0.13	0.13
V	**0.97**	0.13	0.15
Cr	**0.96**	0.12	0.16
Mn	**0.97**	0.12	0.13
Fe	**0.96**	0.14	0.12
Cu	**0.98**	0.12	0.14
Zn	**0.97**	0.14	0.13
Br	0.19	-0.07	**0.88**
Sn	0.40	0.20	-0.02
Ba	**0.97**	0.13	0.12
Pb	**0.98**	0.11	0.13
Expl.Var	12.08	2.33	1.49
Prp.Totl	0.60	0.12	0.07
Eigenvalue	13.06	1.81	1.02
Var. %	65.30	9.07	5.11
Cum. %	65.30	74.37	79.48

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

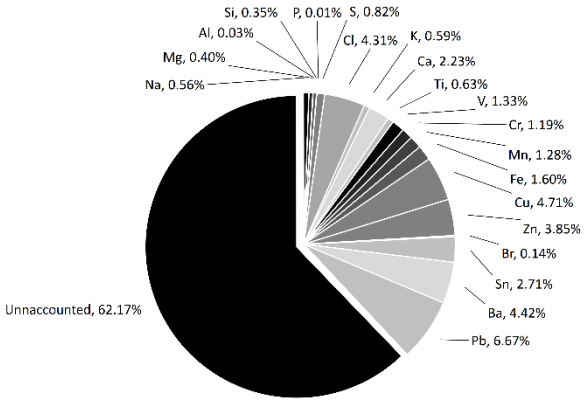
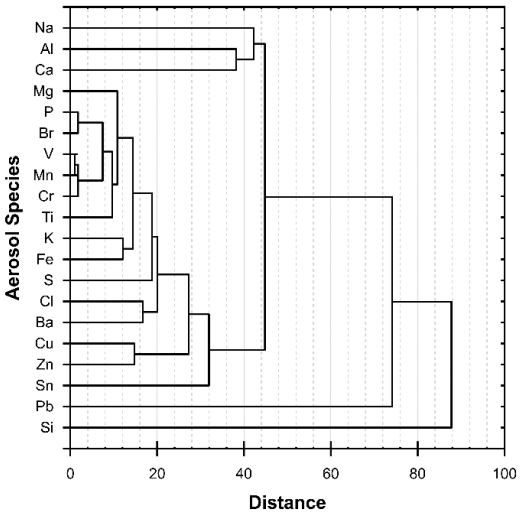


Figure D.5. The summer source characterisation results for the residential indoor environment of ISFB households, within the coal-burning settlement of KwaDela, in South Africa (N=144) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

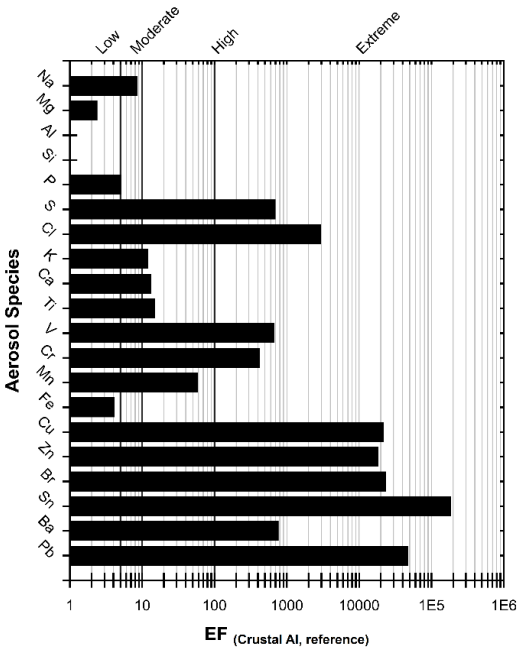
A **PCA (Varimax Rotated)**

Receptor	C-KZ			
Source	Crustal Soil	Road Traffic	Solid Fuel Comb.	Waste Burning
	F1	F2	F3	F4
Na	**0.68**	0.49	0.01	0.07
Mg	**0.90**	0.16	0.22	-0.05
Al	**0.98**	-0.01	0.00	0.00
Si	**0.98**	-0.03	0.04	0.00
P	**0.90**	-0.05	-0.03	-0.05
S	**0.52**	-0.10	**-0.51**	0.10
Cl	0.22	**0.90**	-0.31	0.05
K	**0.87**	0.25	-0.09	-0.04
Ca	**0.88**	0.01	0.09	0.00
Ti	**0.63**	0.05	**0.70**	-0.09
V	0.05	**0.99**	0.00	0.05
Cr	0.06	**0.98**	-0.07	0.05
Mn	0.08	**0.98**	0.04	0.04
Fe	**0.88**	0.28	0.08	0.02
Cu	-0.02	**0.92**	0.27	-0.15
Zn	0.24	**0.51**	0.00	-0.37
Br	0.02	-0.07	0.44	0.23
Sn	-0.03	-0.09	0.03	**-0.90**
Ba	0.03	**0.99**	0.01	0.04
Pb	0.10	0.01	**0.92**	-0.19
Expl.Var	7.11	6.20	2.03	1.10
Prp.Totl	0.36	0.31	0.10	0.05
Eigenvalue	8.11	5.25	2.06	1.02
Var. %	40.57	26.24	10.31	5.09
Cum. %	40.57	66.81	77.12	82.21

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

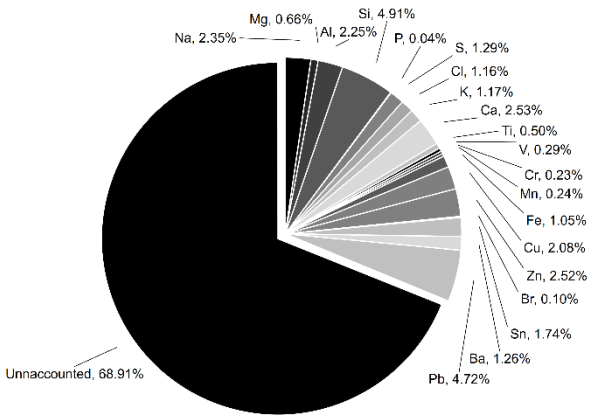
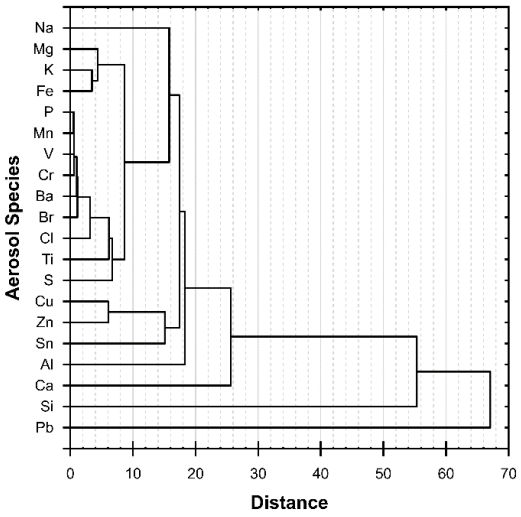


Figure D.6. The source characterisation results for the residential indoor environment within the coal-burning settlement of KwaZamokuhle, in South Africa (N=245) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

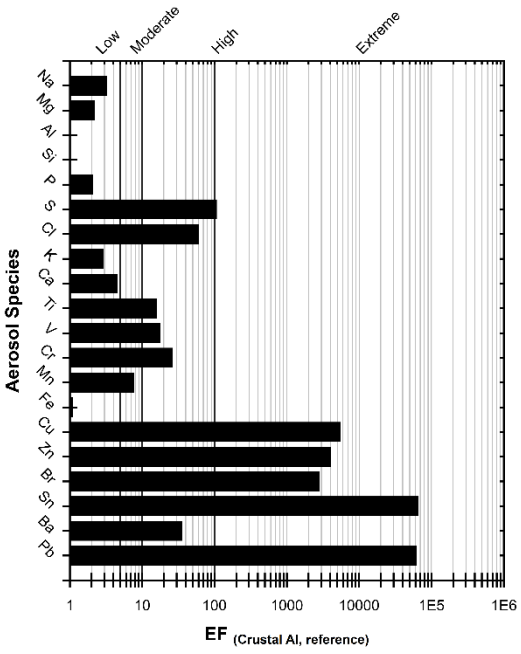
A **PCA (Varimax Rotated)**

Receptor	C-KZ-S				
Source	Crustal Soil	Road Traffic	Waste Burn.	Solid Fuel Comb.	Solid Fuel Comb.
	F1	F2	F3	F4	F5
Na	**0.91**	0.05	0.06	0.10	0.00
Mg	**0.97**	0.07	0.09	0.10	0.02
Al	**0.98**	0.08	0.03	0.13	0.00
Si	**0.99**	0.07	0.07	0.11	0.01
P	**0.96**	0.09	-0.03	0.17	0.02
S	0.33	-0.11	-0.12	**0.50**	-0.35
Cl	**0.97**	0.06	0.03	0.06	0.02
K	**0.97**	0.08	0.10	0.11	0.00
Ca	**0.96**	0.04	0.09	0.08	0.03
Ti	**0.94**	0.23	0.06	0.12	0.00
V	0.38	0.00	0.40	0.41	0.07
Cr	0.08	0.08	-0.04	**0.87**	0.10
Mn	**0.60**	0.03	0.37	-0.03	0.28
Fe	**0.97**	0.08	0.06	0.15	-0.01
Cu	0.07	**0.92**	0.05	0.10	0.08
Zn	0.48	**0.56**	-0.11	-0.06	-0.03
Br	0.09	0.25	**0.52**	0.08	-0.38
Sn	-0.03	0.08	**-0.85**	0.12	-0.02
Ba	-0.13	-0.08	0.05	-0.07	**-0.87**
Pb	0.04	**0.91**	0.04	-0.03	0.01
Expl.Var	10.13	2.18	1.37	1.36	1.13
Prp.Totl	0.51	0.11	0.07	0.07	0.06
Eigenvalue	10.63	2.01	1.32	1.18	1.02
Var. %	53.17	10.05	6.61	5.92	5.11
Cum. %	53.17	63.21	69.82	75.74	80.85

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

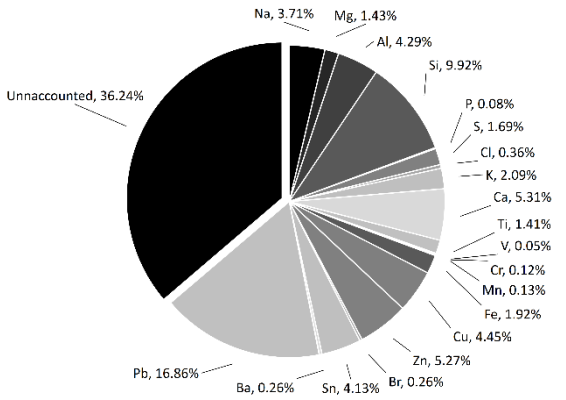
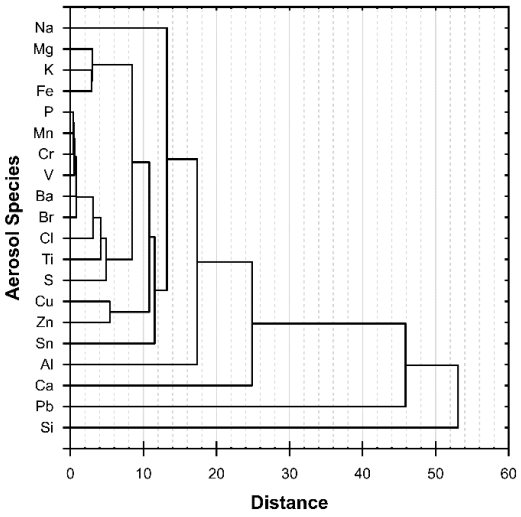


Figure D.7. The summer source characterisation results for the residential indoor environment within the coal-burning settlement of KwaZamokuhle, in South Africa (N=73) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

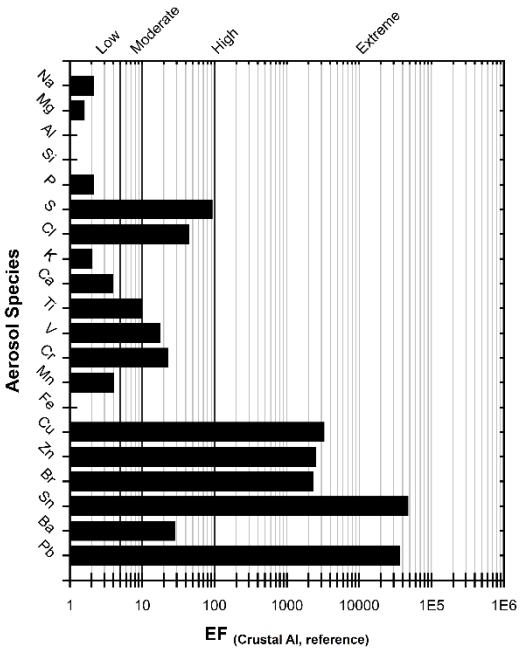
A **PCA (Varimax Rotated)**

Receptor	C-KZ-S-ISFB			
Source	Crustal Soil	Road Traffic	Solid Fuel Comb.	Waste Burning
	F1	F2	F3	F4
Na	**0.95**	0.07	-0.04	0.04
Mg	**0.97**	0.10	0.01	0.07
Al	**0.98**	0.13	-0.03	0.02
Si	**0.99**	0.11	-0.01	0.04
P	**0.97**	0.14	-0.08	0.00
S	0.41	-0.18	0.12	0.02
Cl	**0.98**	0.10	-0.02	-0.04
K	**0.98**	0.12	0.01	0.07
Ca	**0.96**	0.08	0.02	0.07
Ti	**0.95**	0.25	-0.01	0.06
V	0.48	0.01	0.16	0.43
Cr	0.01	0.19	-0.20	**0.79**
Mn	**0.75**	0.01	-0.03	0.23
Fe	**0.98**	0.12	-0.02	0.05
Cu	0.08	**0.91**	0.00	0.23
Zn	0.42	**0.61**	0.06	-0.26
Br	0.12	0.37	**0.63**	-0.16
Sn	-0.19	0.16	**-0.60**	**-0.52**
Ba	-0.23	-0.08	**0.73**	-0.07
Pb	0.04	**0.92**	0.01	0.08
Expl.Var	10.66	2.45	1.39	1.32
Prp.Totl	0.53	0.12	0.07	0.07
Eigenvalue	11.00	2.18	1.40	1.24
Var. %	54.98	10.92	7.00	6.21
Cum. %	54.98	65.90	72.90	79.11

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

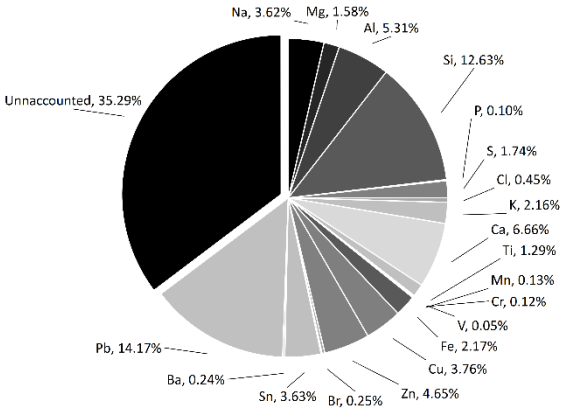
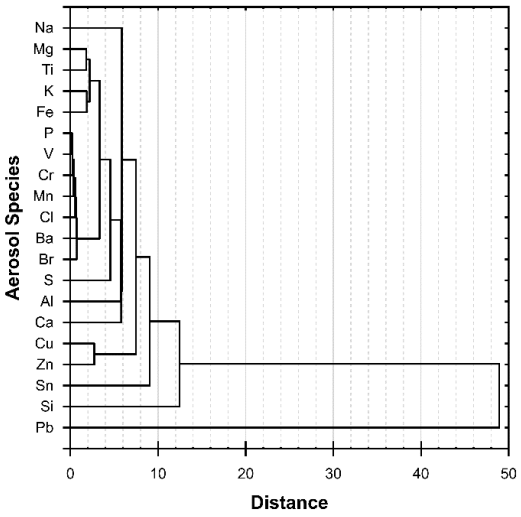


Figure D.8. The summer source characterisation results for the residential indoor environment of ISFB households, within the coal-burning settlement of KwaZamokuhle, in South Africa (N=36). including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

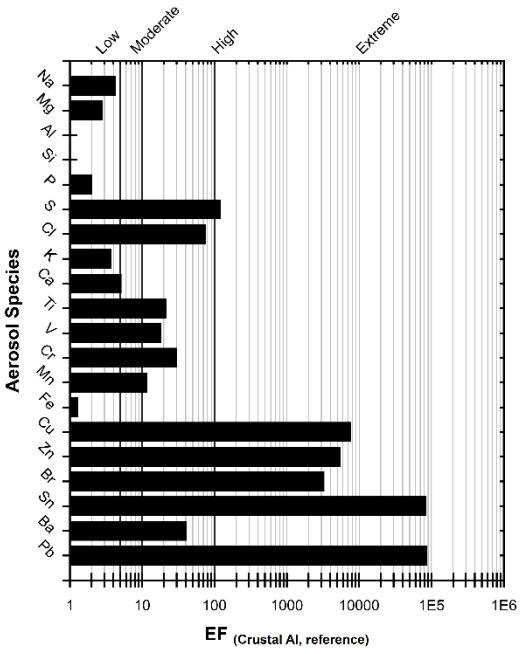
A **PCA (Varimax Rotated)**

Receptor	C-KZ-S-NSFB				
Source	Crustal Soil	Solid Fuel Comb.	Road Traffic	Waste Burn.	Waste Burn.
	F1	F2	F3	F4	F5
Na	**0.83**	0.04	0.10	0.14	0.01
Mg	**0.71**	0.23	0.24	0.24	0.00
Al	**0.96**	0.05	0.03	0.04	0.11
Si	**0.97**	0.03	0.05	0.03	0.09
P	**0.83**	0.03	-0.08	0.17	0.12
S	0.23	0.08	0.13	0.18	**0.81**
Cl	0.44	0.28	0.43	0.12	-0.29
K	**0.90**	-0.04	0.19	0.08	0.00
Ca	0.49	0.22	0.01	0.33	0.03
Ti	**0.69**	**0.50**	0.10	-0.10	0.24
V	0.14	0.04	**0.77**	0.23	0.17
Cr	0.39	-0.17	0.10	0.48	-0.04
Mn	-0.05	0.17	-0.13	**-0.75**	0.00
Fe	**0.97**	0.08	0.04	0.01	0.06
Cu	0.06	**0.88**	0.00	-0.04	-0.11
Zn	0.33	0.45	-0.43	0.04	-0.48
Br	0.18	-0.09	**0.73**	-0.29	-0.03
Sn	0.11	0.05	-0.18	**0.79**	0.12
Ba	0.30	-0.28	-0.32	-0.14	0.43
Pb	0.10	**0.92**	0.01	-0.17	0.06
Expl.Var	6.89	2.42	1.80	1.89	1.32
Prp.Totl	0.34	0.12	0.09	0.09	0.07
Eigenvalue	7.45	2.48	1.70	1.54	1.15
Var. %	37.27	12.40	8.51	7.68	5.73
Cum. %	37.27	49.67	58.18	65.87	71.59

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

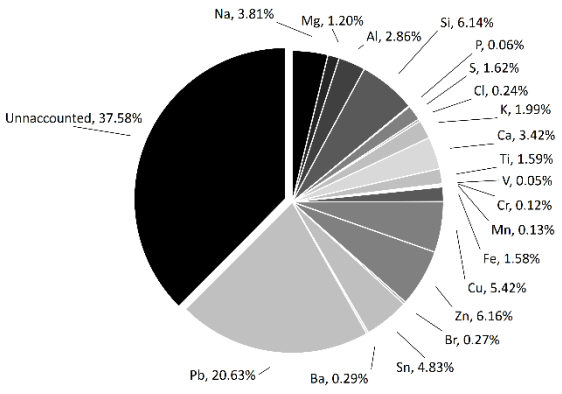
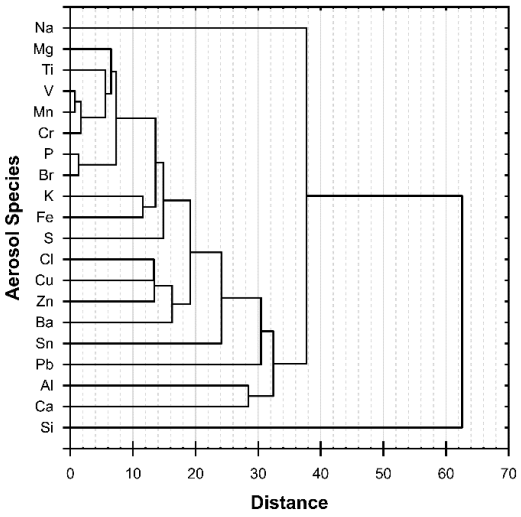


Figure D.9. The summer source characterisation results for the residential indoor environment of NSFB households, within the coal-burning settlement of KwaZamokuhle, in South Africa (N=37) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

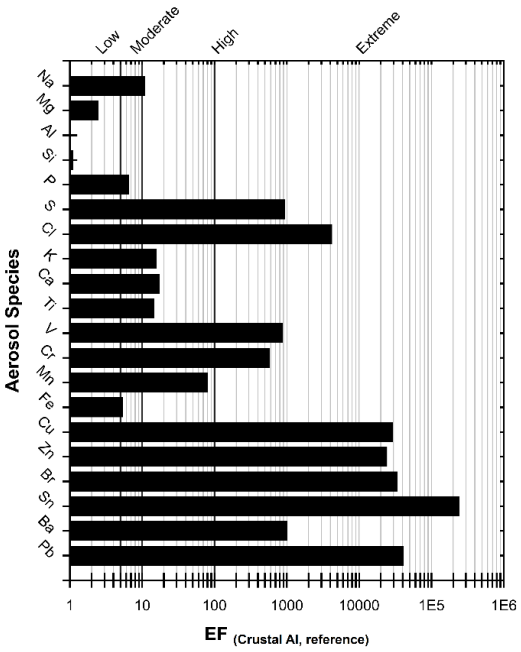
A **PCA (Varimax Rotated)**

Receptor	C-KZ-W			
Source	Solid Fuel Comb.	Crustal Soil	Road Traffic	Waste Burning
	F1	F2	F3	F4
Na	**0.53**	**0.59**	0.13	0.01
Mg	0.37	**0.83**	0.07	-0.06
Al	-0.04	**0.96**	0.14	0.05
Si	-0.05	**0.97**	0.12	0.02
P	-0.07	**0.86**	0.01	-0.18
S	-0.27	**0.70**	-0.02	0.21
Cl	**0.94**	0.19	-0.11	-0.03
K	0.31	**0.80**	-0.18	-0.09
Ca	0.05	**0.78**	0.06	0.07
Ti	0.28	**0.65**	**0.66**	0.02
V	**0.98**	0.04	0.18	0.01
Cr	**0.97**	0.05	0.17	0.02
Mn	**0.97**	0.05	0.19	0.01
Fe	0.37	**0.73**	0.38	0.09
Cu	**0.99**	-0.03	-0.04	0.01
Zn	**0.66**	0.13	**-0.51**	0.06
Br	-0.05	-0.10	0.30	**-0.72**
Sn	0.01	0.06	-0.22	**-0.70**
Ba	**0.98**	0.02	0.18	0.01
Pb	**0.53**	0.33	**0.72**	-0.02
Expl.Var	7.22	6.51	1.71	1.13
Prp.Totl	0.36	0.33	0.09	0.06
Eigenvalue	8.78	5.26	1.41	1.12
Var. %	43.91	26.31	7.04	5.58
Cum. %	43.91	70.22	77.26	82.84

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

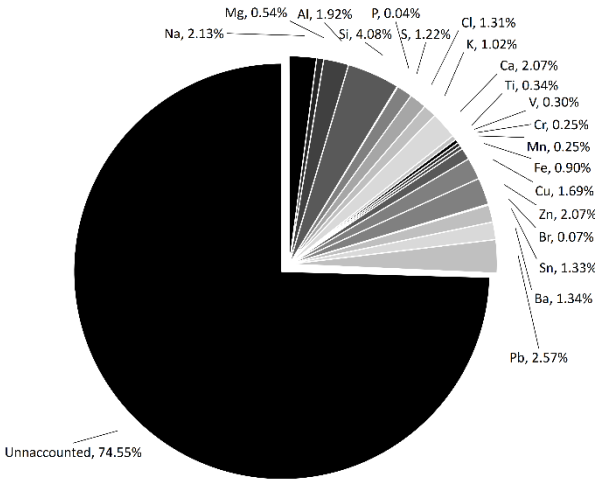
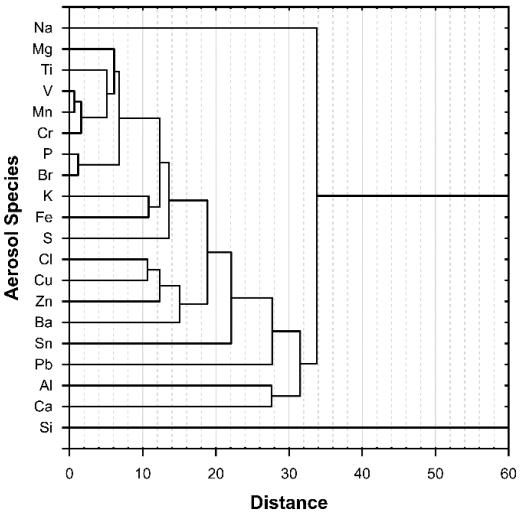


Figure D.10. The winter source characterisation results for the residential indoor environment within the coal-burning settlement of KwaZamokuhle, in South Africa (N=172) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

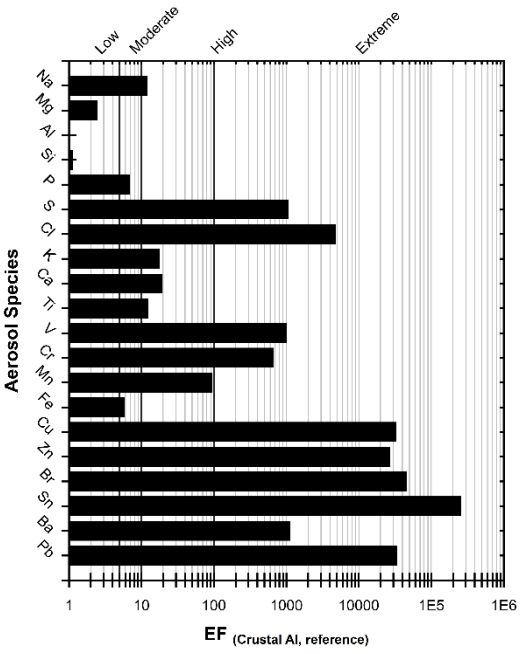
A **PCA (Varimax Rotated)**

Receptor	C-KZ-W-ISFB		
Source	Solid Fuel Comb.	Crustal Soil	Waste Burning
	F1	F2	F3
Na	**0.54**	**0.60**	0.05
Mg	0.32	**0.85**	0.05
Al	-0.08	**0.97**	0.01
Si	-0.09	**0.97**	0.03
P	-0.10	**0.90**	0.13
S	-0.34	**0.69**	0.12
Cl	**0.95**	0.11	0.17
K	0.24	**0.75**	0.31
Ca	-0.02	**0.78**	-0.01
Ti	0.38	**0.79**	-0.36
V	**0.99**	0.05	-0.08
Cr	**0.98**	0.05	-0.07
Mn	**0.99**	0.07	-0.08
Fe	0.40	**0.80**	-0.15
Cu	**0.98**	-0.08	0.10
Zn	**0.58**	-0.04	**0.60**
Br	0.07	-0.06	-0.31
Sn	0.02	0.02	**0.54**
Ba	**0.99**	0.03	-0.08
Pb	**0.66**	0.49	-0.42
Expl.Var	7.43	7.00	1.27
Prp.Totl	0.37	0.35	0.06
Eigenvalue	8.65	5.78	1.27
Var. %	43.25	28.88	6.34
Cum. %	43.25	72.13	78.47

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

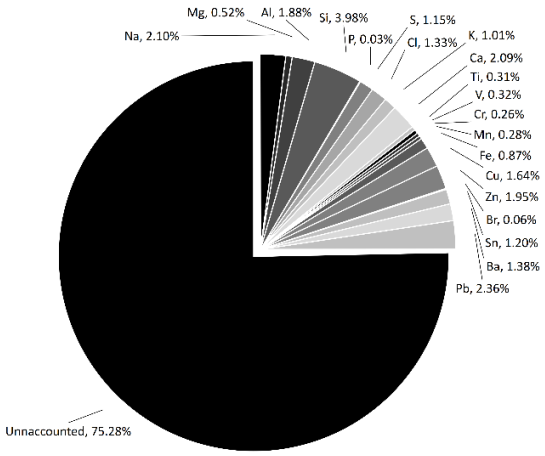
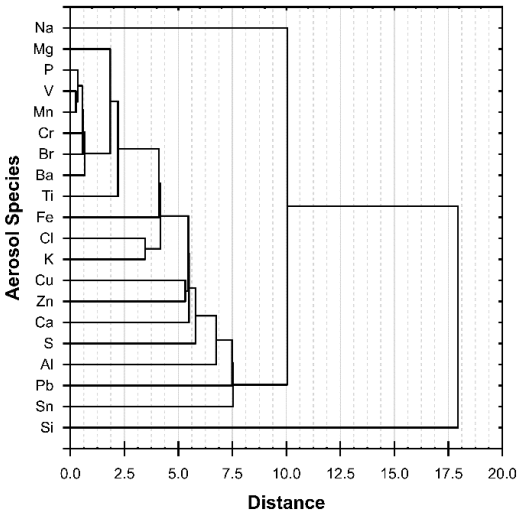


Figure D.11. The winter source characterisation results for the residential indoor environment of ISFB households, within the coal-burning settlement of KwaZamokuhle, in South Africa (N=144) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

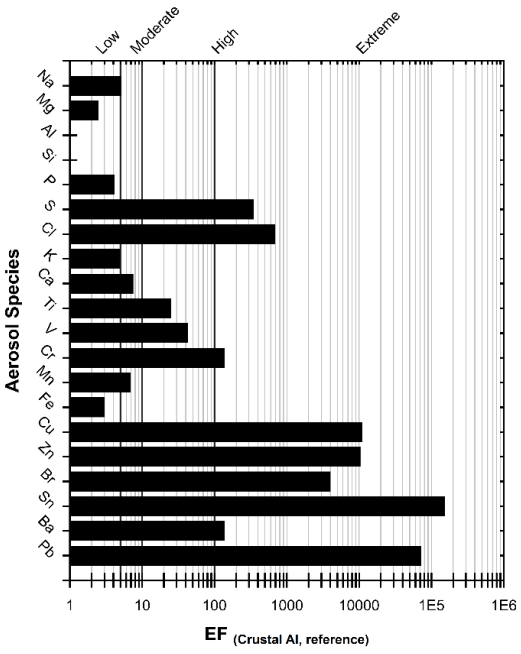
A **PCA (Varimax Rotated)**

Receptor	C-KZ-W-NSFB				
Source	Crustal Soil	Road Traffic	Solid Fuel Comb.	Waste Burn.	Solid Fuel Comb.
	F1	F2	F3	F4	F5
Na	**0.73**	-0.04	0.11	-0.10	0.35
Mg	**0.84**	0.16	-0.16	0.31	-0.15
Al	**0.65**	0.06	**0.69**	0.10	0.18
Si	**0.68**	0.04	**0.67**	0.10	0.14
P	**0.73**	0.15	0.23	0.36	-0.10
S	**0.36**	-0.03	0.44	-0.31	**0.57**
Cl	**0.94**	0.07	-0.11	-0.09	-0.03
K	**0.84**	-0.01	0.31	0.05	-0.02
Ca	**0.76**	0.29	0.28	-0.12	0.00
Ti	0.31	**0.60**	**0.62**	-0.05	0.19
V	-0.06	-0.09	**0.79**	0.08	-0.19
Cr	0.15	0.28	0.15	-0.26	**0.54**
Mn	0.12	**0.52**	0.10	0.49	0.15
Fe	0.16	0.24	**0.83**	0.07	0.22
Cu	0.05	**0.94**	-0.05	-0.03	0.05
Zn	-0.03	**0.90**	0.13	-0.10	-0.09
Br	0.09	-0.10	0.14	**0.75**	-0.06
Sn	0.03	-0.23	-0.02	**0.84**	-0.05
Ba	-0.25	-0.10	-0.11	0.20	**0.86**
Pb	0.22	**0.87**	0.02	-0.28	0.02
Expl.V.	5.24	3.43	3.16	2.09	1.72
Prp.Totl	0.26	0.17	0.16	0.10	0.09
Eigenv.	7.00	3.17	2.21	1.92	1.34
Var. %	35.02	15.84	11.05	9.59	6.71
Cum. %	35.02	50.86	61.91	71.50	78.21

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

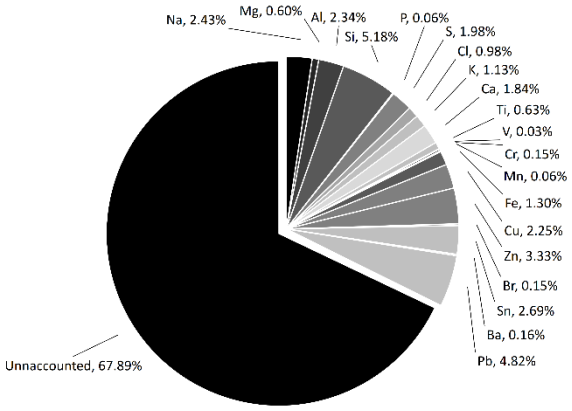
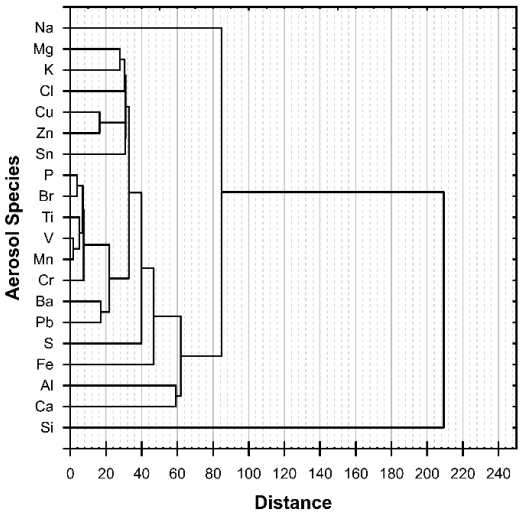


Figure D.12. The winter source characterisation results for the residential indoor environment of NSFB households, within the coal-burning settlement of KwaZamokuhle, in South Africa (N=28) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

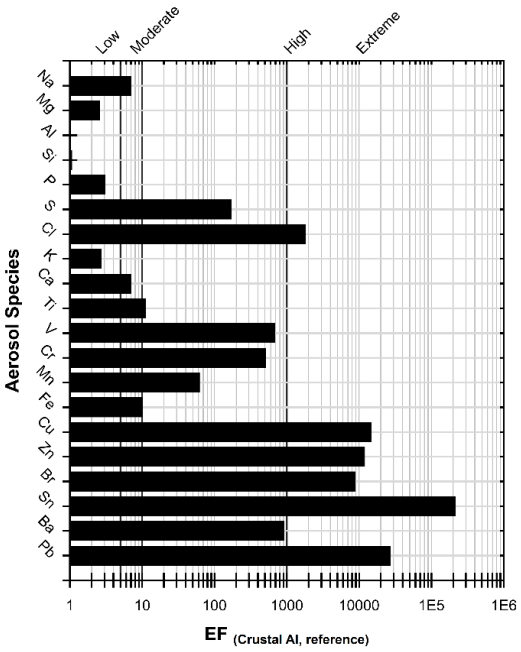
A **PCA (Varimax Rotated)**

Receptor	U			
Source	Crustal Soil	Solid Fuel Comb.	Road Traffic	Waste Burning
	F1	F2	F3	F4
Na	**0.74**	0.34	-0.04	-0.04
Mg	**0.83**	0.16	-0.02	0.17
Al	**0.95**	0.05	0.05	-0.18
Si	**0.94**	-0.01	0.06	-0.17
P	**0.93**	-0.01	0.05	0.18
S	0.41	0.07	0.02	-0.33
Cl	**0.51**	0.64	0.04	0.38
K	**0.87**	0.07	0.02	0.25
Ca	**0.84**	0.16	0.05	0.16
Ti	**0.60**	**0.65**	0.13	-0.27
V	0.07	**0.99**	0.07	0.03
Cr	0.11	**0.71**	0.12	-0.17
Mn	0.16	**0.97**	0.08	-0.03
Fe	**0.69**	0.10	0.19	**-0.50**
Cu	0.03	**0.68**	**0.70**	0.05
Zn	0.10	0.23	**0.92**	0.02
Br	0.12	-0.01	0.09	**0.53**
Sn	0.02	0.00	**0.89**	0.06
Ba	0.05	**0.99**	0.07	0.03
Pb	0.05	**0.99**	0.07	0.03
Expl.Var	6.66	5.92	2.23	1.12
Prp.Totl	0.33	0.30	0.11	0.06
Eigenvalue	8.42	4.50	1.89	1.12
Var. %	42.10	22.52	9.43	5.59
Cum. %	42.10	64.62	74.05	79.64

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

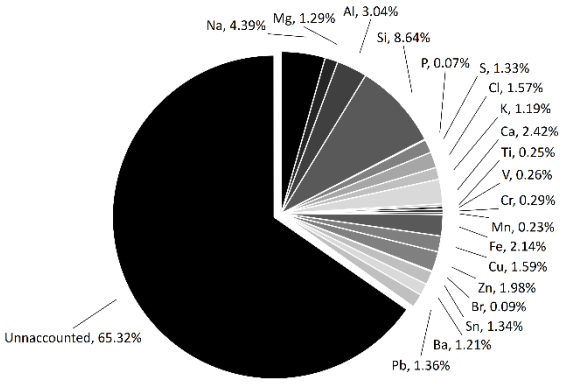
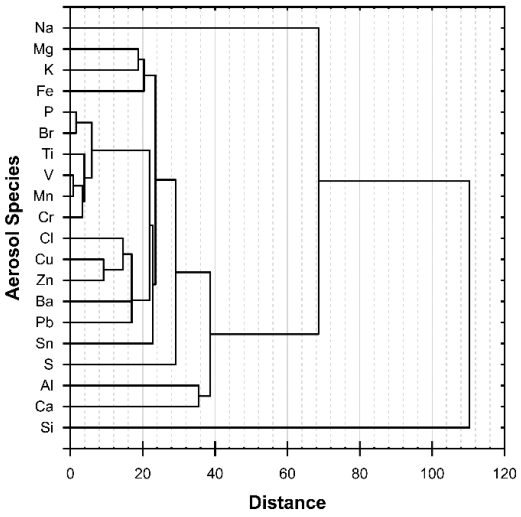


Figure D.13. The source characterisation results for the residential indoor environment of within the urbanised-burning settlement of Jouberton, in South Africa (N=1156) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

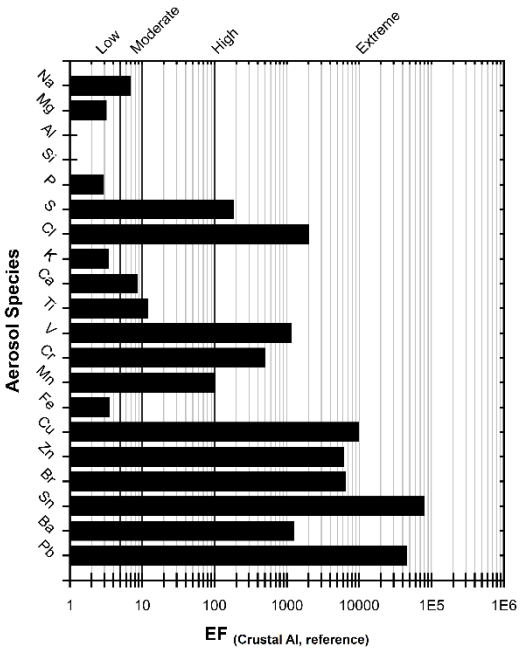
A **PCA (Varimax Rotated)**

Receptor	U-S		
Source	Road Traffic	Crustal Soil	Waste Burning
	F1	F2	F3
Na	0.40	**0.76**	-0.16
Mg	0.14	**0.78**	-0.01
Al	0.15	**0.96**	-0.01
Si	0.11	**0.97**	0.01
P	-0.02	**0.91**	0.06
S	-0.22	0.45	0.32
Cl	**0.85**	0.31	0.07
K	0.13	**0.88**	0.04
Ca	0.13	**0.83**	0.12
Ti	**0.78**	**0.59**	0.05
V	**0.98**	0.10	0.10
Cr	**0.88**	0.11	0.20
Mn	**0.97**	0.17	0.10
Fe	0.36	**0.87**	0.07
Cu	**0.86**	0.08	0.45
Zn	0.53	0.18	**0.70**
Br	0.14	-0.07	0.44
Sn	0.11	0.08	**0.79**
Ba	**0.98**	0.08	0.09
Pb	**0.98**	0.06	0.11
Expl.Var	7.42	6.85	1.76
Prp.Totl	0.37	0.34	0.09
Eigenvalue	9.88	4.76	1.39
Var. %	49.42	23.79	6.96
Cum. %	49.42	73.21	80.17

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

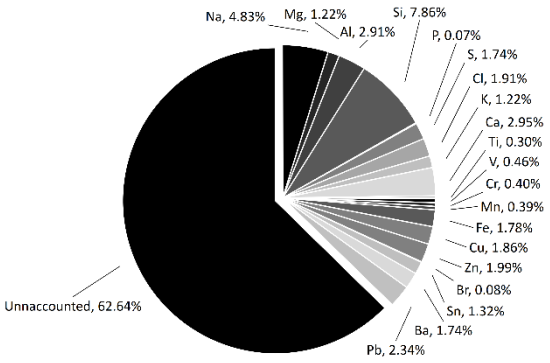
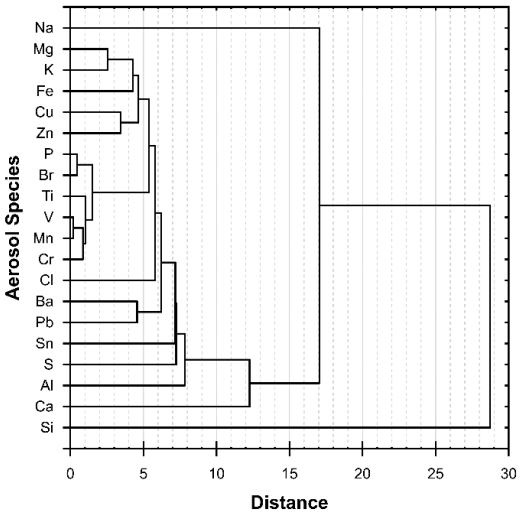


Figure D.14. The summer source characterisation results for the residential indoor environment within the urbanised-burning settlement of Jouberton, in South Africa (N=570) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

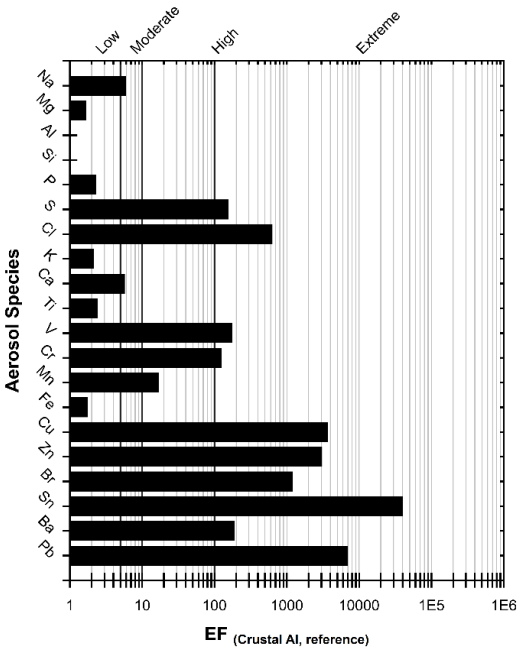
A **PCA (Varimax Rotated)**

Receptor	U-JN-S-ISFB			
Source	Road Traffic	Crustal Soil	Waste Burning	Biomass Burn
	F1	F2	F3	F4
Na	**0.61**	0.45	-0.08	0.09
Mg	0.18	**0.90**	0.00	-0.06
Al	0.18	**0.94**	-0.02	-0.01
Si	0.12	**0.96**	0.00	-0.03
P	-0.05	**0.87**	0.01	0.12
S	-0.16	**0.55**	0.01	0.28
Cl	**0.80**	-0.01	-0.06	0.01
K	0.30	**0.86**	-0.09	0.11
Ca	-0.18	**0.70**	0.09	-0.27
Ti	**0.92**	0.34	0.01	0.04
V	**0.99**	0.06	0.02	0.04
Cr	**0.94**	-0.02	0.06	-0.09
Mn	**0.99**	0.09	0.02	0.03
Fe	**0.55**	**0.74**	0.00	-0.08
Cu	**0.91**	0.03	0.37	-0.07
Zn	0.21	0.10	**0.83**	-0.28
Br	-0.08	-0.05	0.02	**-0.80**
Sn	-0.08	-0.13	**0.71**	0.43
Ba	**0.99**	0.05	0.02	0.04
Pb	**0.99**	0.05	0.02	0.04
Expl.Var	8.06	5.82	1.37	1.12
Prp.Totl	0.40	0.29	0.07	0.06
Eigenvalue	9.01	4.90	1.33	1.12
Var. %	45.04	24.52	6.65	5.62
Cum. %	45.04	69.57	76.21	81.83

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

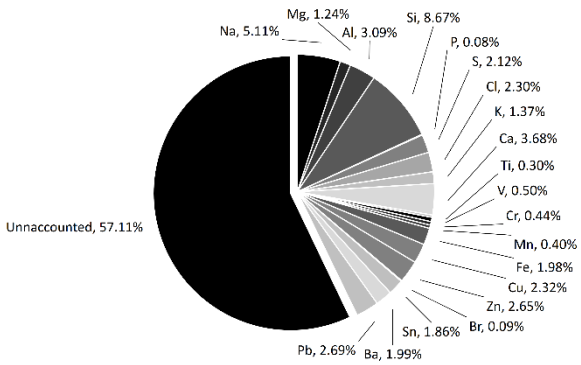
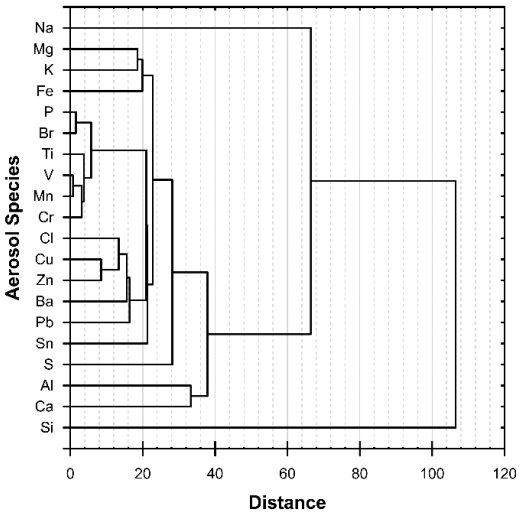


Figure D.15. The summer source characterisation results for the residential indoor environment of ISFB households, within the urbanised-burning settlement of Jouberton, in South Africa (N=70) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

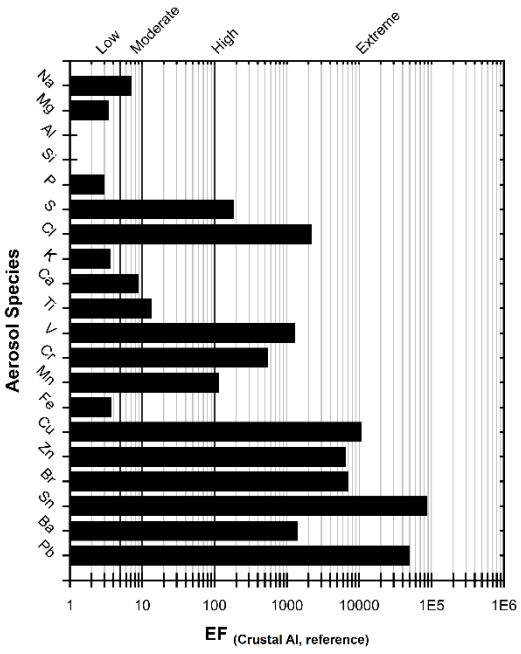
A **PCA (Varimax Rotated)**

Receptor	U-JN-S-NSFB		
Source	Road Traffic	Crustal Soil	Waste Burning
	F1	F2	F3
Na	0.39	**0.77**	-0.17
Mg	0.14	**0.78**	-0.01
Al	0.14	**0.97**	0.00
Si	0.10	**0.97**	0.02
P	-0.02	**0.91**	0.07
S	-0.23	0.44	0.36
Cl	**0.85**	0.34	0.09
K	0.12	**0.88**	0.06
Ca	0.15	**0.83**	0.12
Ti	**0.77**	**0.61**	0.05
V	**0.98**	0.10	0.10
Cr	**0.88**	0.11	0.20
Mn	**0.97**	0.17	0.10
Fe	0.35	**0.88**	0.08
Cu	**0.86**	0.07	0.45
Zn	**0.55**	0.18	**0.68**
Br	0.17	-0.08	0.45
Sn	0.14	0.09	**0.79**
Ba	**0.98**	0.08	0.09
Pb	**0.98**	0.07	0.11
Expl.Var	7.42	6.93	1.78
Prp.Totl	0.37	0.35	0.09
Eigenvalue	9.97	4.78	1.38
Var. %	49.87	23.90	6.90
Cum. %	49.87	73.77	80.67

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

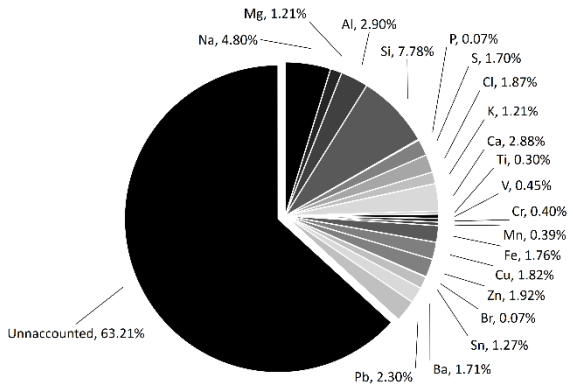
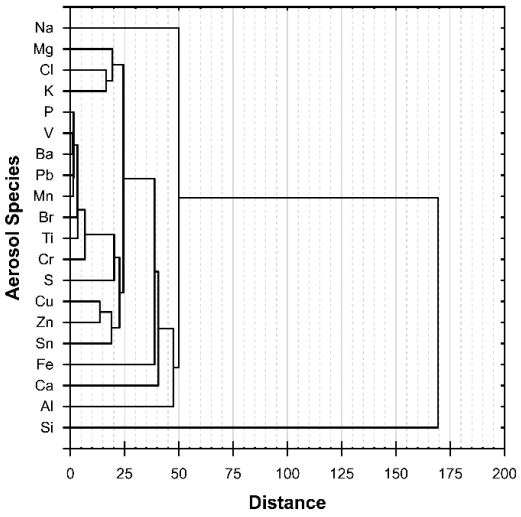


Figure D.16. The summer source characterisation results for the residential indoor environment of NSFB households, within the urbanised-burning settlement of Jouberton, in South Africa (N=500) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

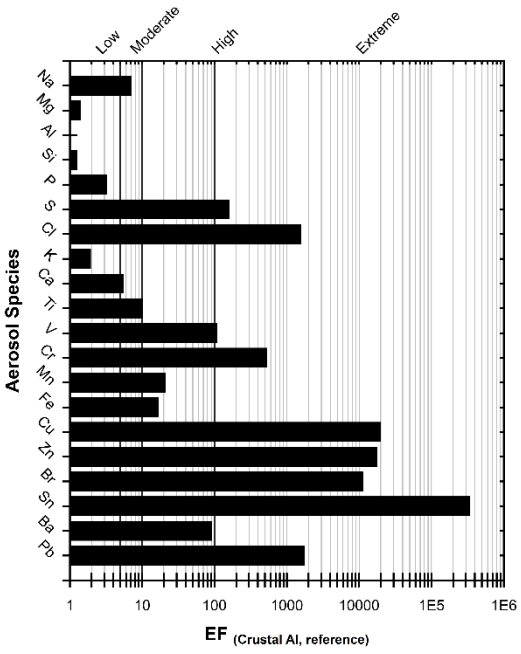
A **PCA (Varimax Rotated)**

Receptor	U-W				
Source	Crustal Soil	Road Traf.	Solid Fuel Comb	Waste Burn	Bio. Burn
	F1	F2	F3	F4	F5
Na	**0.73**	-0.02	0.24	0.05	0.06
Mg	**0.88**	-0.02	0.20	-0.05	-0.02
Al	**0.77**	0.00	**0.55**	0.05	0.03
Si	**0.76**	0.01	**0.56**	0.04	0.02
P	**0.93**	0.03	0.25	0.02	-0.02
S	0.33	-0.04	0.48	0.12	0.12
Cl	**0.89**	0.02	-0.17	0.05	-0.07
K	**0.91**	0.02	0.12	0.05	-0.03
Ca	0.86	0.00	0.24	-0.06	-0.03
Ti	0.36	0.03	**0.86**	0.08	0.01
V	0.02	0.01	**0.54**	-0.22	-0.14
Cr	0.09	0.01	-0.01	**0.92**	0.03
Mn	0.24	0.05	**0.85**	0.02	0.02
Fe	0.26	0.07	**0.79**	0.44	0.02
Cu	0.01	**0.97**	0.01	0.02	0.01
Zn	0.06	**0.96**	0.08	0.03	0.01
Br	0.17	-0.04	0.00	-0.03	**-0.88**
Sn	0.03	0.90	-0.01	-0.03	-0.05
Ba	-0.18	0.41	0.02	0.15	-0.43
Pb	-0.08	0.05	0.27	0.31	-0.19
Expl.V.	6.14	2.85	3.58	1.24	1.04
Prp.Totl	0.31	0.14	0.18	0.06	0.05
Eigenv.	7.70	2.90	2.12	1.13	1.02
Var. %	38.48	14.50	10.58	5.64	5.10
Cum. %	38.48	52.98	63.56	69.20	74.30

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

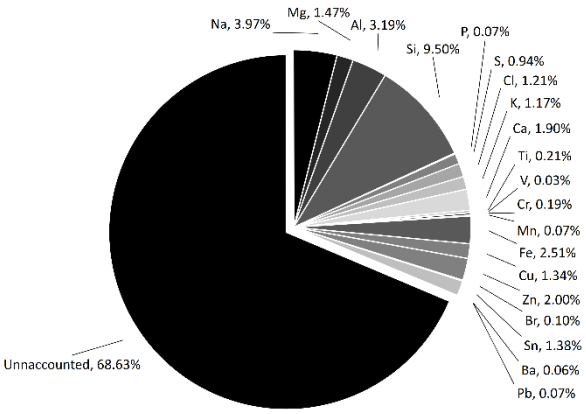
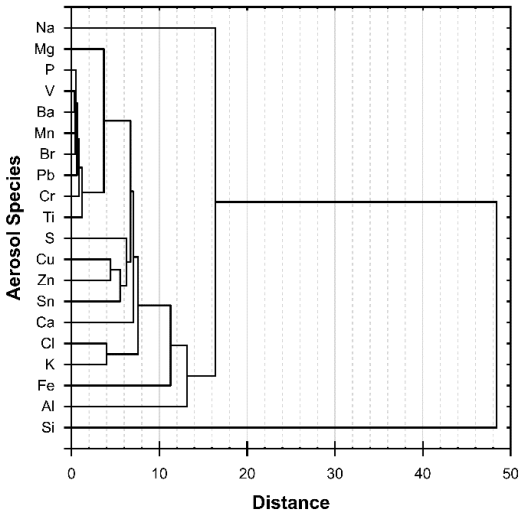


Figure D.17. The winter source characterisation results for the residential indoor environment within the urbanised-burning settlement of Jouberton, in South Africa (N=59) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

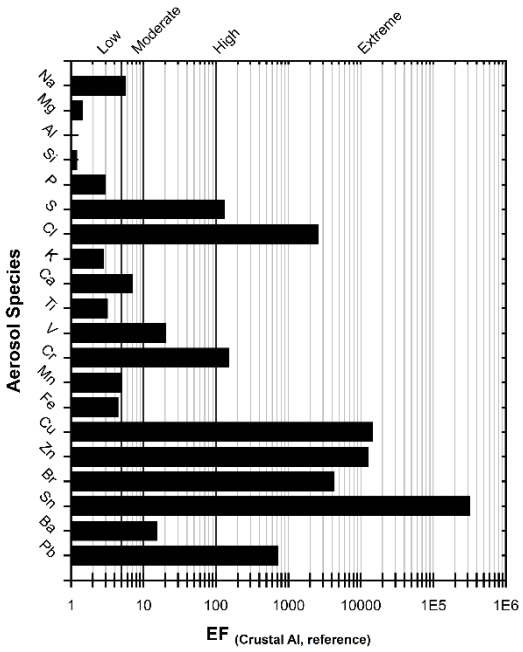
A **PCA (Varimax Rotated)**

Receptor	U-JN-W-ISFB				
Source	Bio. Burn	Crustal Soil	Road Traffic	Waste Burn	Solid Fuel Comb
	F1	F2	F3	F4	F5
Na	**0.73**	0.18	-0.08	0.26	0.29
Mg	**0.76**	-0.16	0.12	-0.37	-0.20
Al	0.45	**0.79**	-0.11	0.03	0.07
Si	0.47	**0.76**	-0.02	0.02	0.23
P	**0.89**	0.26	0.11	-0.12	0.05
S	0.28	**0.58**	-0.04	-0.05	**0.52**
Cl	**0.91**	-0.15	0.13	0.08	0.11
K	**0.89**	-0.01	0.11	0.13	0.15
Ca	**0.88**	0.08	0.01	-0.15	-0.10
Ti	-0.08	**0.94**	0.08	-0.02	0.00
V	-0.11	0.43	0.47	-0.43	-0.18
Cr	-0.18	0.22	0.49	-0.05	**0.52**
Mn	-0.09	**0.82**	0.19	0.02	-0.08
Fe	-0.13	**0.93**	0.16	0.01	0.06
Cu	0.14	-0.03	**0.90**	0.19	0.08
Zn	0.28	0.19	**0.89**	0.10	0.08
Br	0.17	-0.10	0.11	0.07	**0.68**
Sn	0.08	-0.18	0.12	**0.53**	**-0.51**
Ba	-0.07	-0.06	0.05	**0.64**	0.06
Pb	-0.01	0.32	0.13	0.49	-0.07
Expl.Var	5.01	4.53	2.25	1.45	1.55
Prp.Totl	0.25	0.23	0.11	0.07	0.08
Eigenvalue	5.88	4.07	2.09	1.40	1.35
Var. %	29.41	20.35	10.43	7.02	6.77
Cum. %	29.41	49.76	60.19	67.21	73.98

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

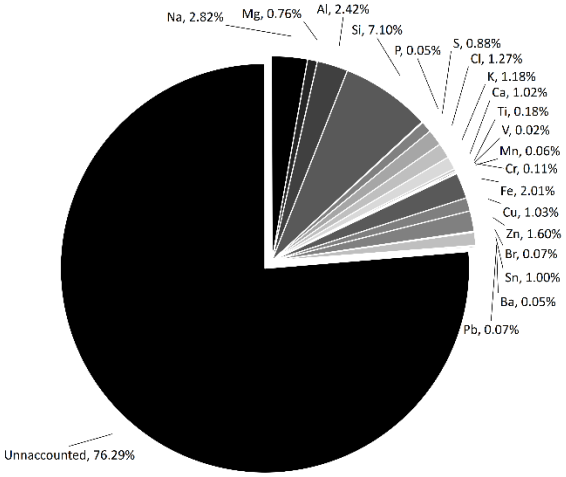
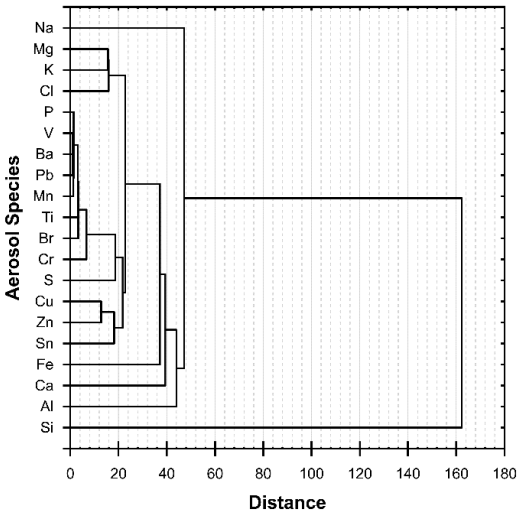


Figure D.18. The winter source characterisation results for the residential indoor environment of ISFB households, within the urbanised-burning settlement of Jouberton, in South Africa (N=527) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

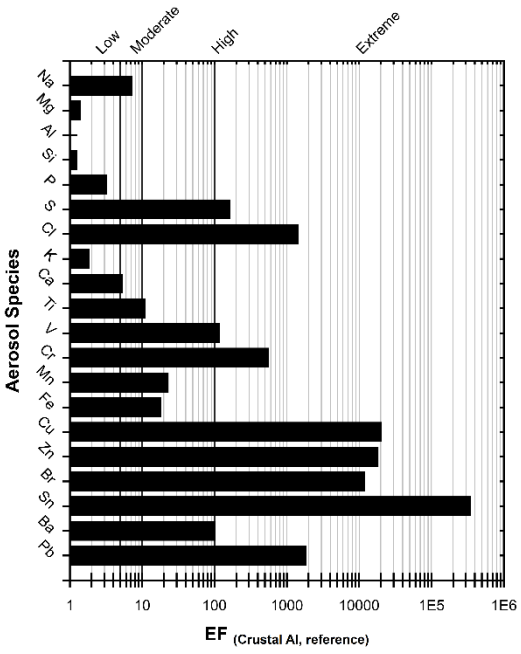
A **PCA (Varimax Rotated)**

Receptor	U-JN-W-NSFB				
Source	Crustal Soil	Road Traffic	Solid Fuel Comb	Waste Burn	Bio. Burn
	F1	F2	F3	F4	F5
Na	**0.74**	-0.03	0.23	0.02	-0.11
Mg	**0.91**	-0.02	0.17	-0.03	0.06
Al	**0.82**	0.01	0.48	0.01	-0.04
Si	**0.80**	0.01	**0.50**	0.00	-0.04
P	**0.94**	0.03	0.22	0.02	0.04
S	0.35	-0.03	0.47	0.03	-0.23
Cl	**0.89**	0.01	-0.17	0.09	0.07
K	**0.93**	0.01	0.15	0.05	0.03
Ca	**0.88**	-0.01	0.20	-0.04	0.07
Ti	0.45	0.03	**0.82**	0.02	-0.03
V	0.06	-0.01	**0.52**	-0.24	0.23
Cr	0.08	0.01	0.05	**0.94**	0.01
Mn	0.30	0.05	**0.84**	-0.04	-0.05
Fe	0.32	0.07	**0.79**	0.41	-0.03
Cu	0.01	**0.97**	0.01	0.02	-0.02
Zn	0.06	**0.96**	0.07	0.02	-0.03
Br	0.16	-0.02	0.01	-0.01	**0.86**
Sn	0.03	**0.91**	0.00	-0.03	0.03
Ba	-0.20	0.44	0.09	0.11	0.39
Pb	-0.10	0.06	0.33	0.22	0.10
Expl.Var	6.60	2.90	3.32	1.19	1.05
Prp.Totl	0.33	0.14	0.17	0.06	0.05
Eigenvalue	7.98	2.95	1.96	1.14	1.03
Var. %	39.92	14.73	9.81	5.69	5.16
Cum. %	39.92	54.64	64.45	70.14	75.30

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

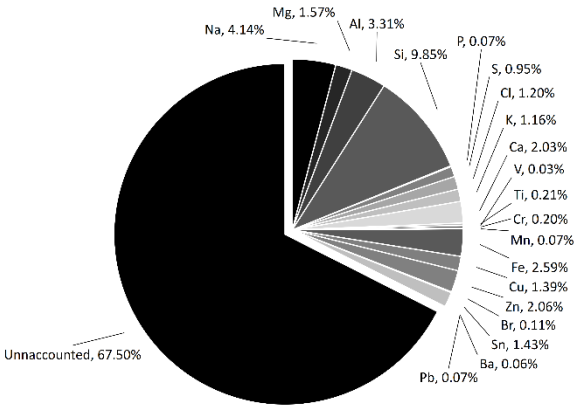
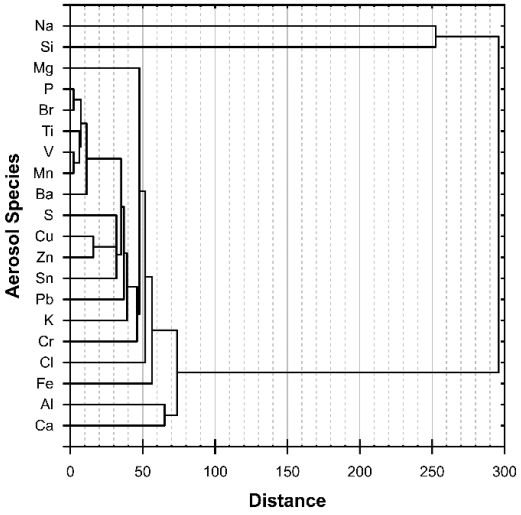


Figure D.19. The winter source characterisation results for the residential indoor environment of NSFB households, within the urbanised-burning settlement of Jouberton, in South Africa (N=28) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

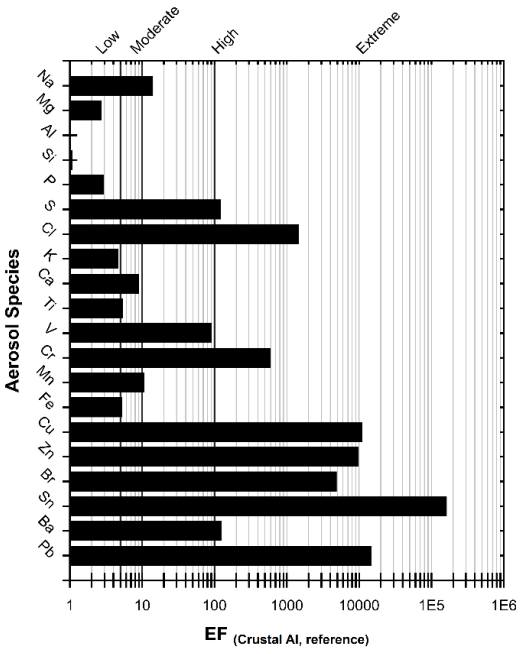
A **PCA (Varimax Rotated)**

Receptor	W				
Source	Crustal Soil	Road Traffic	Road Traffic	Bio. Burn	Waste Burn
	F1	F2	F3	F4	F5
Na	0.46	0.18	-0.03	**0.80**	-0.05
Mg	**0.72**	-0.03	0.01	0.33	0.04
Al	**0.92**	0.22	0.04	0.10	-0.02
Si	**0.94**	0.13	0.02	0.14	0.00
P	**0.89**	0.06	0.02	0.03	0.06
S	**0.59**	0.04	0.00	0.07	0.02
Cl	0.25	0.15	-0.04	**0.89**	-0.01
K	**0.90**	0.10	0.02	0.15	0.02
Ca	**0.83**	0.12	0.04	0.04	0.04
Ti	**0.70**	**0.64**	0.09	0.00	0.01
V	0.10	**0.97**	0.07	0.06	-0.07
Cr	-0.05	0.12	**0.99**	0.05	-0.03
Mn	0.20	**0.92**	0.21	0.08	-0.08
Fe	0.15	0.13	**0.97**	0.05	-0.02
Cu	0.11	**0.88**	-0.03	0.10	0.37
Zn	0.17	0.34	-0.06	0.10	**0.76**
Br	0.00	-0.06	0.06	0.21	0.07
Sn	-0.03	-0.15	-0.01	0.04	**0.71**
Ba	0.08	**0.97**	0.08	0.05	-0.08
Pb	0.07	**0.84**	0.02	-0.10	0.05
Expl.Var	5.77	4.92	2.00	1.69	1.26
Prp.Totl	0.29	0.25	0.10	0.08	0.06
Eigenvalue	7.54	3.69	1.92	1.30	1.18
Var. %	37.70	18.46	9.62	6.48	5.91
Cum. %	37.70	56.16	65.77	72.26	78.16

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

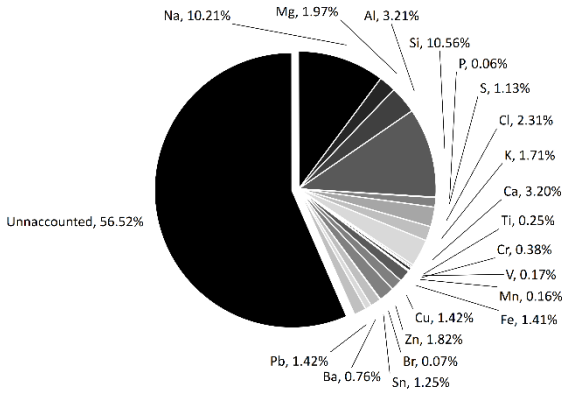
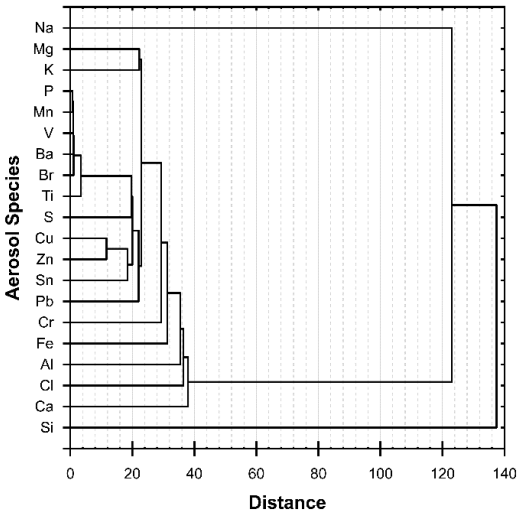


Figure D.20. The source characterisation results for the residential indoor environment within the low-income wood-burning communities in South Africa (N=1321) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

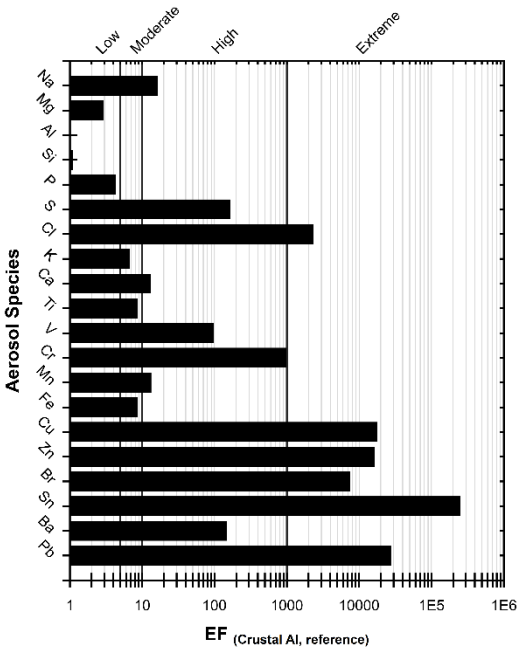
A **PCA (Varimax Rotated)**

Receptor	W-S				
Source	Crustal Soil	Road Traffic	Road Traffic	Bio. Burn	Waste Burn
	F1	F2	F3	F4	F5
Na	0.35	-0.05	-0.04	**0.88**	0.04
Mg	**0.67**	0.10	0.01	**0.54**	0.01
Al	**0.92**	-0.04	0.00	0.22	-0.12
Si	**0.92**	-0.02	-0.01	0.23	-0.12
P	**0.82**	0.01	0.01	0.13	0.05
S	0.41	-0.11	-0.01	0.40	-0.08
Cl	0.29	-0.03	-0.01	**0.84**	0.14
K	**0.87**	-0.03	0.01	0.22	-0.06
Ca	**0.86**	0.08	0.01	0.14	0.01
Ti	**0.82**	-0.02	0.17	-0.01	0.47
V	0.17	0.33	0.24	0.06	-0.10
Cr	-0.08	0.03	**0.98**	-0.01	0.02
Mn	**0.82**	0.14	-0.03	0.04	-0.10
Fe	0.07	0.03	**0.98**	0.04	0.01
Cu	0.04	**0.95**	-0.09	0.08	0.10
Zn	0.12	**0.94**	-0.06	0.10	0.11
Br	0.00	0.09	0.05	0.26	-0.11
Sn	-0.12	0.13	-0.10	0.15	**0.53**
Ba	-0.20	0.42	0.14	-0.18	0.06
Pb	0.03	0.03	0.12	-0.27	**0.87**
Expl.Var	6.15	2.16	2.08	2.33	1.38
Prp.Totl	0.31	0.11	0.10	0.12	0.07
Eigenvalue	7.00	2.28	2.08	1.52	1.22
Var. %	35.00	11.38	10.38	7.59	6.12
Cum. %	35.00	46.39	56.77	64.37	70.49

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

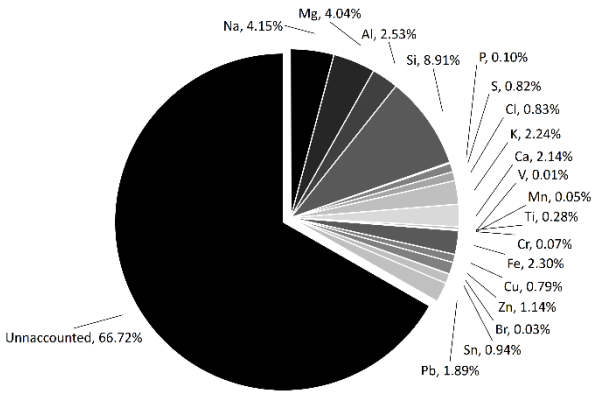
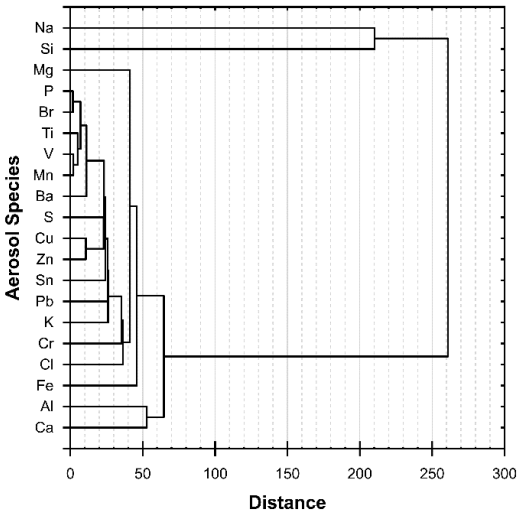


Figure D.21. The summer source characterisation results for the residential indoor environment within the low-income wood-burning communities in South Africa (N=654) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

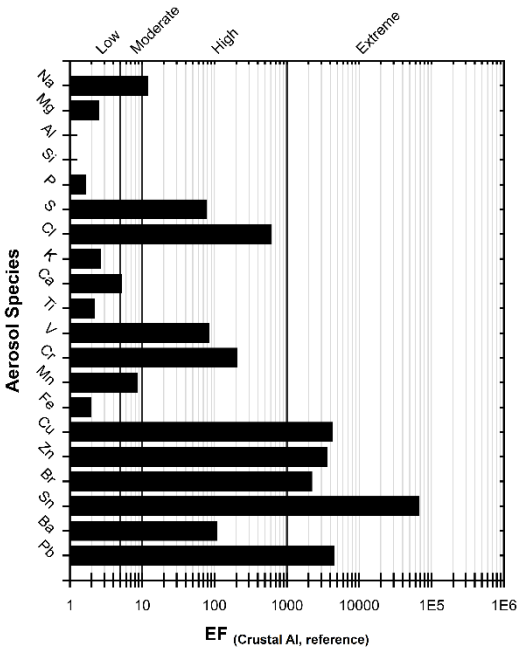
A **PCA (Varimax Rotated)**

Receptor	W-W				
Source	Crustal Soil	Road Traffic	Road Traffic	Bio. Burn	Waste Burn
	F1	F2	F3	F4	F5
Na	0.32	0.05	0.02	**0.89**	0.01
Mg	**0.65**	-0.17	-0.01	0.34	0.00
Al	**0.92**	0.22	0.05	0.11	-0.04
Si	**0.94**	0.07	0.03	0.17	-0.01
P	**0.90**	0.03	0.00	0.09	0.00
S	**0.54**	-0.03	0.00	-0.18	0.25
Cl	0.11	0.17	0.01	**0.95**	0.04
K	**0.90**	0.06	0.02	0.17	0.05
Ca	**0.81**	0.11	0.04	0.05	-0.05
Ti	**0.64**	**0.70**	0.07	0.07	-0.08
V	0.00	**0.97**	0.10	0.06	-0.11
Cr	-0.04	0.13	**0.98**	0.01	0.03
Mn	0.08	**0.92**	0.30	0.07	-0.09
Fe	0.14	0.13	**0.97**	0.02	0.03
Cu	0.06	**0.96**	-0.04	0.10	0.13
Zn	0.28	**0.50**	-0.16	0.13	**0.54**
Br	-0.01	-0.05	0.11	0.00	0.34
Sn	-0.02	-0.14	-0.10	0.02	**0.78**
Ba	0.00	**0.97**	0.11	0.06	-0.12
Pb	0.02	**0.93**	-0.02	-0.02	-0.07
Expl.Var	5.35	5.43	2.08	1.95	1.15
Prp.Totl	0.27	0.27	0.10	0.10	0.06
Eigenvalue	6.88	4.42	1.97	1.59	1.12
Var. %	34.39	22.09	9.84	7.94	5.58
Cum. %	34.39	56.48	66.32	74.26	79.84

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

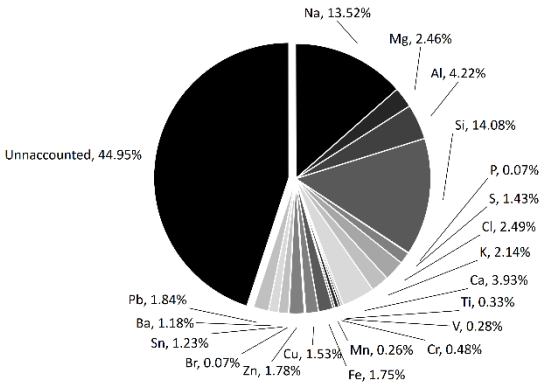
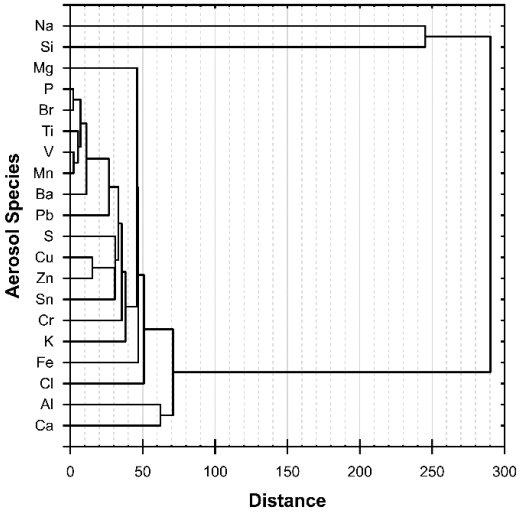


Figure D.22. The winter source characterisation results for the residential indoor environment within the low-income wood-burning communities in South Africa (N=658) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

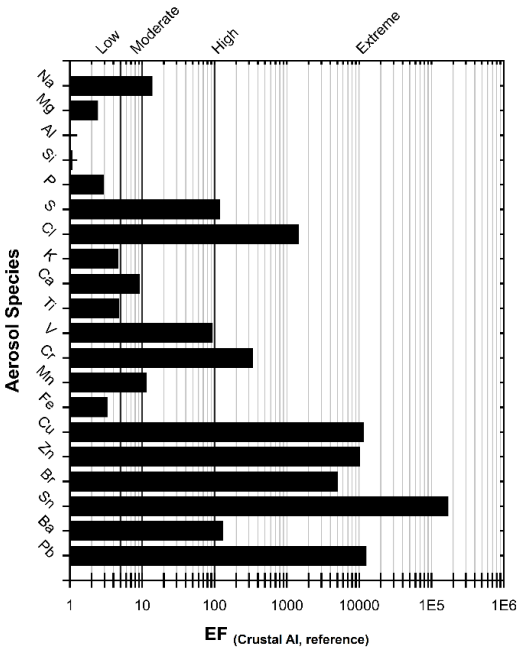
A **PCA (Varimax Rotated)**

Receptor	W-AG				
Source	Crustal Soil	Road Traffic	Road Traffic	Bio. Burn	Waste Burn
	F1	F2	F3	F4	F5
Na	0.45	0.17	0.02	**0.81**	-0.02
Mg	**0.71**	-0.04	0.02	0.38	0.05
Al	**0.93**	0.22	0.06	0.10	-0.01
Si	**0.94**	0.13	0.04	0.15	0.01
P	**0.89**	0.07	0.02	0.07	0.03
S	**0.58**	0.04	0.03	0.06	0.05
Cl	0.25	0.14	-0.02	**0.90**	0.00
K	**0.90**	0.10	0.04	0.16	0.02
Ca	**0.84**	0.12	0.05	0.04	0.03
Ti	**0.70**	**0.66**	0.07	0.06	-0.04
V	0.11	**0.97**	0.10	0.05	-0.06
Cr	-0.02	0.16	**0.98**	0.04	-0.02
Mn	0.20	**0.92**	0.28	0.06	-0.06
Fe	0.19	0.17	**0.96**	0.06	-0.01
Cu	0.12	**0.89**	-0.01	0.07	0.37
Zn	0.18	0.34	-0.05	0.07	**0.77**
Br	-0.01	-0.07	0.09	0.18	0.13
Sn	-0.03	-0.15	-0.01	0.02	**0.69**
Ba	0.09	**0.97**	0.11	0.05	-0.06
Pb	0.06	**0.94**	-0.01	-0.01	-0.05
Expl.Var	5.79	5.17	2.01	1.73	1.24
Prp.Totl	0.29	0.26	0.10	0.09	0.06
Eigenvalue	7.84	3.81	1.85	1.29	1.17
Var. %	39.18	19.06	9.23	6.43	5.83
Cum. %	39.18	58.24	67.47	73.90	79.73

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

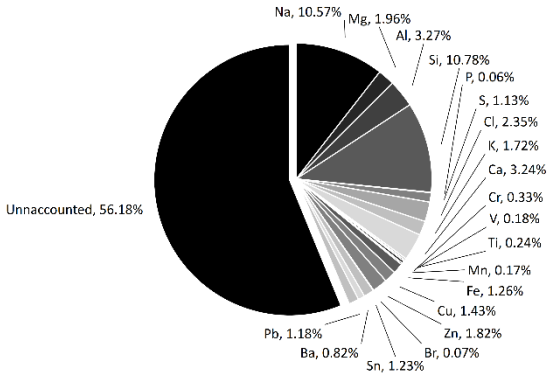
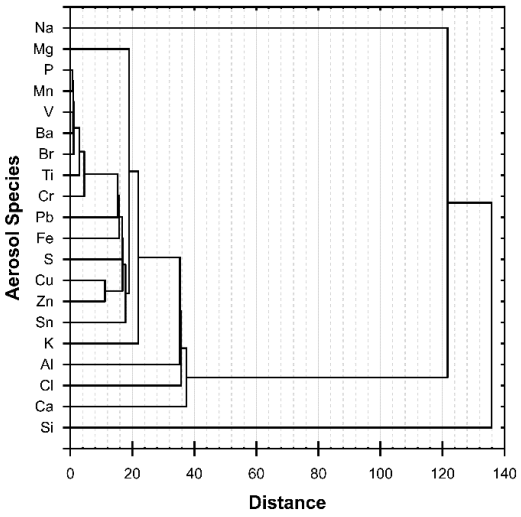


Figure D.23. The source characterisation results for the residential indoor environment within the wood-burning settlement of Agincourt, in South Africa (N=1211) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

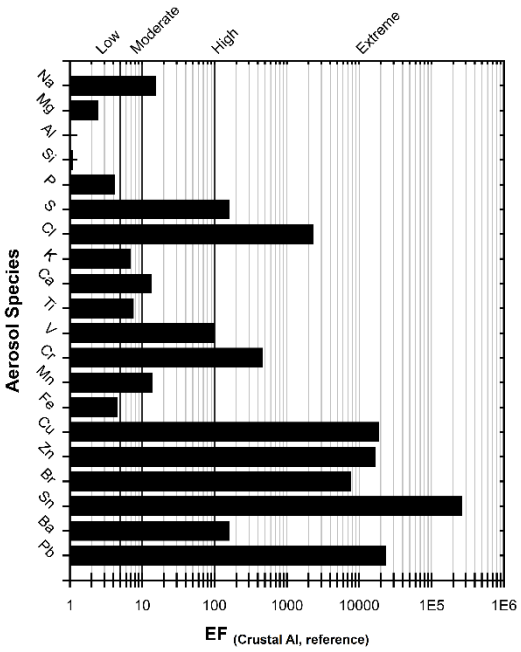
A **PCA (Varimax Rotated)**

Receptor	W-AG-S				
Source	Crustal Soil	Road Traffic	Bio. Burn	Solid Fuel Burn	Road Traffic
	F1	F2	F3	F4	F5
Na	0.34	0.00	**0.88**	0.04	0.06
Mg	**0.67**	0.13	**0.53**	0.09	0.13
Al	**0.92**	-0.04	0.22	0.13	0.03
Si	**0.92**	-0.02	0.23	0.13	0.03
P	**0.81**	0.02	0.16	-0.04	-0.02
S	0.41	-0.08	0.39	0.16	0.00
Cl	0.28	0.00	**0.86**	-0.05	0.04
K	**0.86**	-0.01	0.24	0.07	-0.02
Ca	**0.86**	0.08	0.15	-0.04	0.02
Ti	**0.90**	-0.07	0.07	-0.34	0.03
V	0.19	0.34	0.03	0.11	0.07
Cr	-0.03	0.28	-0.13	0.03	**0.89**
Mn	**0.82**	0.13	0.03	0.09	0.06
Fe	**0.66**	0.15	0.11	0.12	**0.65**
Cu	0.02	**0.94**	0.05	-0.11	0.13
Zn	0.11	**0.93**	0.08	-0.12	0.12
Br	-0.02	-0.07	0.25	-0.08	0.38
Sn	-0.12	0.17	0.19	-0.36	0.00
Ba	-0.19	0.46	-0.19	0.00	-0.08
Pb	0.08	-0.08	-0.21	**-0.91**	0.03
Expl.Var	6.67	2.26	2.37	1.23	1.42
Prp.Totl	0.33	0.11	0.12	0.06	0.07
Eigenvalue	7.64	2.48	1.57	1.18	1.07
Var. %	38.21	12.40	7.87	5.91	5.35
Cum. %	38.21	50.61	58.47	64.39	69.74

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

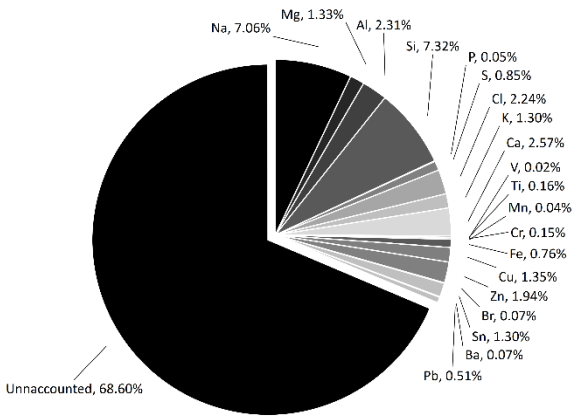
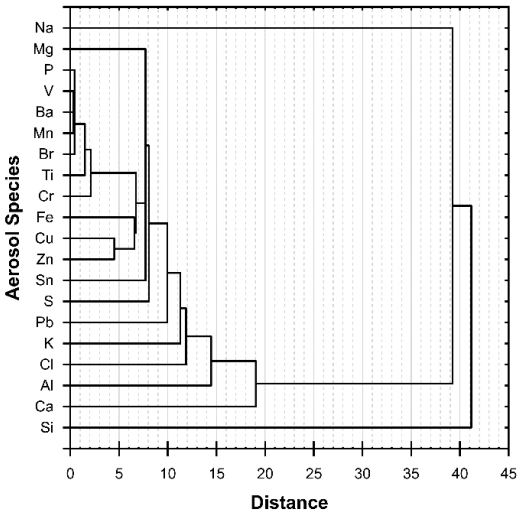


Figure D.24. The summer source characterisation results for the residential indoor environment within the wood-burning settlement of Agincourt, in South Africa (N=602) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

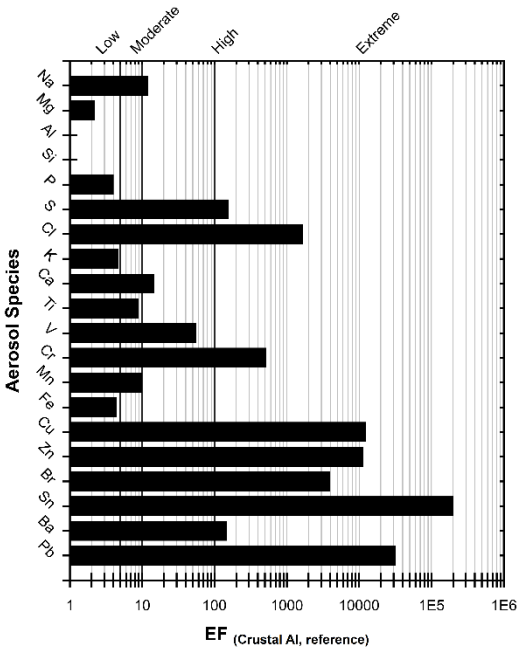
A **PCA (Varimax Rotated)**

Receptor	W-AG-S-ISFB				
Source	Crustal Soil	Road Traffic	Bio. Burn	Solid Fuel Burn	Road Traffic
	F1	F2	F3	F4	F5
Na	**0.74**	0.22	0.21	-0.26	-0.17
Mg	**0.85**	0.15	0.12	-0.16	0.15
Al	**0.92**	0.03	0.21	0.04	-0.01
Si	**0.89**	0.05	0.27	0.03	0.01
P	0.24	0.15	**0.89**	0.07	0.00
S	0.23	-0.04	**0.70**	-0.22	-0.07
Cl	**0.53**	0.30	0.24	-0.17	-0.34
K	0.31	0.16	**0.87**	0.04	-0.01
Ca	**0.78**	0.11	0.16	0.28	0.14
Ti	**0.61**	0.06	0.07	**0.75**	0.00
V	0.15	0.40	0.16	0.05	0.10
Cr	-0.06	0.16	-0.08	0.01	**0.92**
Mn	**0.76**	0.11	0.29	-0.11	0.17
Fe	**0.58**	0.10	0.07	0.00	**0.75**
Cu	0.04	**0.93**	-0.03	0.10	0.02
Zn	0.10	**0.90**	0.14	0.16	0.03
Br	0.16	0.40	0.03	-0.26	0.13
Sn	-0.28	0.23	0.18	0.24	0.16
Ba	-0.35	0.31	-0.15	-0.11	-0.04
Pb	-0.16	0.08	-0.14	**0.89**	0.02
Expl.Var	5.58	2.43	2.53	1.79	1.69
Prp.Totl	0.28	0.12	0.13	0.09	0.08
Eigenvalue	6.84	2.34	1.94	1.60	1.30
Var. %	34.20	11.72	9.68	7.99	6.49
Cum. %	34.20	45.92	55.60	63.59	70.07

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

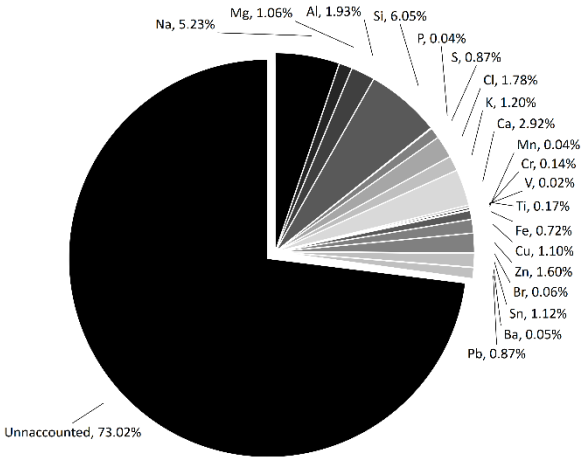
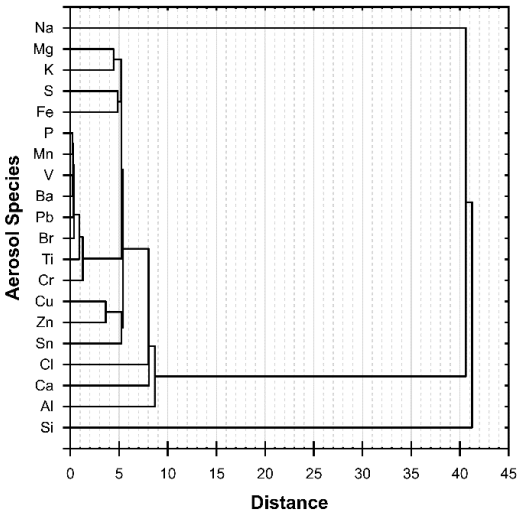


Figure D.25. The summer source characterisation results for the residential indoor environment of ISFB households, within the wood-burning settlement of Agincourt in South Africa (N=96) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

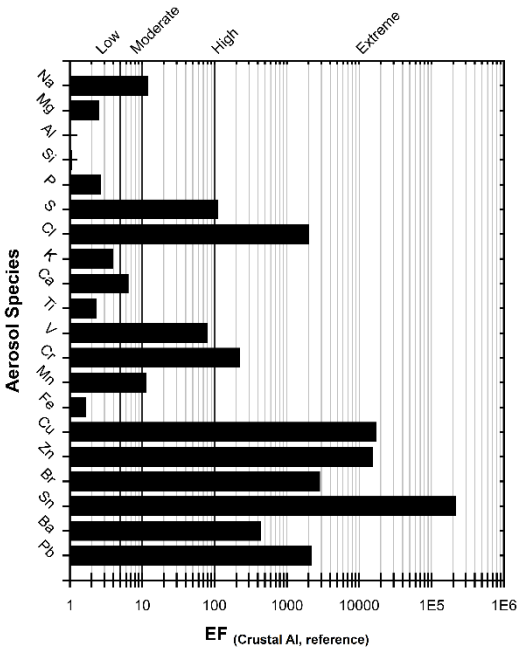
A **PCA (Varimax Rotated)**

Receptor	W-AG-S-NSFB				
Source	Crustal Soil	Road Traffic	Solid Fuel Burn	Bio. Burn	Road Traffic
	F1	F2	F3	F4	F5
Na	**0.67**	0.23	0.04	0.42	0.18
Mg	**0.87**	-0.01	0.05	0.27	0.02
Al	**0.97**	0.00	0.04	-0.10	0.07
Si	**0.98**	0.04	0.04	-0.10	0.08
P	**0.89**	-0.01	0.15	0.04	0.11
S	**0.59**	-0.21	-0.21	0.22	0.06
Cl	**0.74**	0.11	0.06	0.38	0.13
K	**0.96**	-0.03	0.02	0.02	0.07
Ca	**0.90**	0.02	0.22	0.03	0.08
Ti	**0.94**	0.00	0.02	-0.16	-0.01
V	0.28	0.14	0.02	**-0.50**	0.23
Cr	0.00	0.12	0.10	0.06	**0.95**
Mn	**0.73**	-0.02	-0.44	-0.18	0.10
Fe	**0.67**	0.09	0.03	0.01	**0.69**
Cu	-0.15	**0.94**	-0.07	0.01	0.05
Zn	0.15	**0.92**	-0.06	0.06	0.13
Br	0.07	0.07	-0.27	0.61	0.24
Sn	-0.12	0.12	-0.36	0.09	-0.04
Ba	-0.40	-0.18	-0.23	**-0.52**	-0.01
Pb	0.04	-0.04	**-0.89**	-0.02	-0.06
Expl.Var	8.69	1.93	1.38	1.43	1.62
Prp.Totl	0.43	0.10	0.07	0.07	0.08
Eigenvalue	9.00	2.17	1.41	1.30	1.17
Var. %	45.01	10.86	7.03	6.51	5.84
Cum. %	45.01	55.87	62.90	69.41	75.25

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

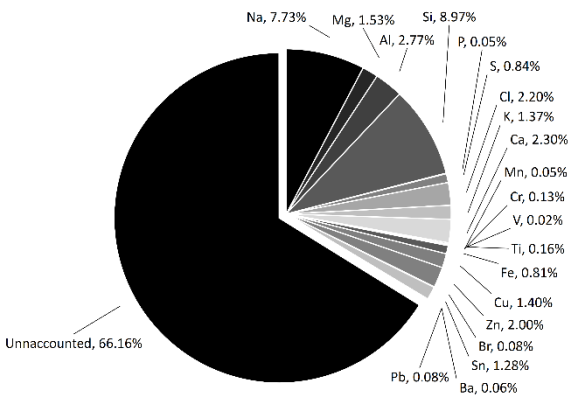
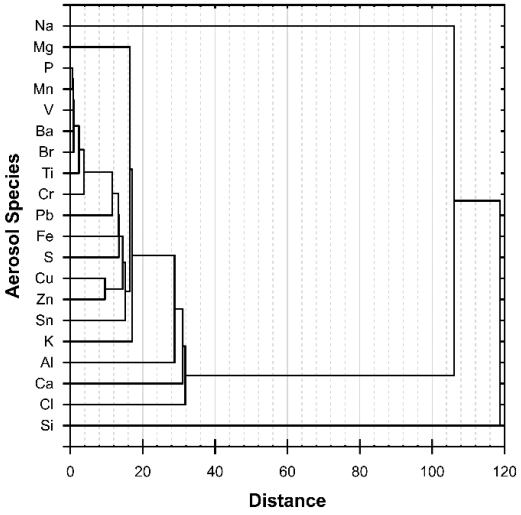


Figure D.26. The summer source characterisation results for the residential indoor environment of NSFB households, within the wood-burning settlement of Agincourt in South Africa (N=66) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

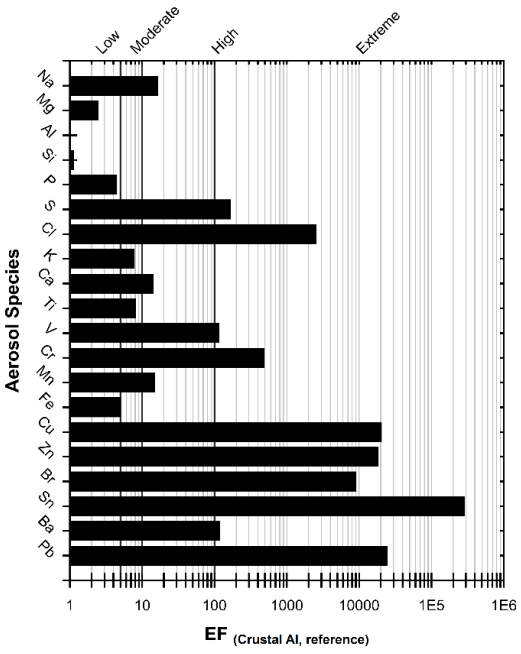
A **PCA (Varimax Rotated)**

Receptor	W-AG-S-OSFB				
Source	Crustal Soil	Road Traffic	Bio. Burn	Solid Fuel Burn	Waste Burn
	F1	F2	F3	F4	F5
Na	0.31	-0.03	**0.90**	0.08	-0.02
Mg	**0.66**	0.14	**0.57**	0.08	0.03
Al	**0.93**	-0.09	0.22	0.11	0.04
Si	**0.93**	-0.07	0.23	0.11	0.03
P	**0.85**	-0.02	0.15	-0.12	0.03
S	0.38	-0.11	0.41	0.15	0.18
Cl	0.24	-0.01	**0.88**	0.00	0.00
K	**0.90**	-0.08	0.24	0.05	0.04
Ca	**0.86**	0.05	0.20	-0.04	-0.01
Ti	**0.91**	-0.05	0.12	-0.27	0.06
V	0.13	0.32	0.06	0.17	0.35
Cr	0.03	**0.61**	-0.14	0.40	0.04
Mn	**0.84**	0.12	0.03	-0.03	0.03
Fe	**0.74**	0.33	0.11	0.36	0.06
Cu	0.04	**0.93**	0.08	-0.07	0.01
Zn	0.10	**0.91**	0.10	-0.08	0.01
Br	-0.05	0.06	0.21	-0.10	**0.67**
Sn	-0.07	0.17	0.20	-0.03	**-0.66**
Ba	-0.15	0.45	-0.15	-0.07	-0.12
Pb	0.06	0.06	-0.14	**-0.87**	0.03
Expl.Var	6.92	2.59	2.47	1.26	1.07
Prp.Totl	0.35	0.13	0.12	0.06	0.05
Eigenvalue	7.87	2.59	1.64	1.17	1.04
Var. %	39.33	12.95	8.20	5.87	5.20
Cum. %	39.33	52.28	60.48	66.35	71.55

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

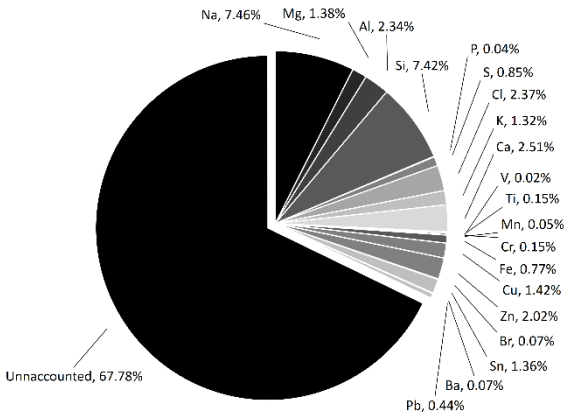
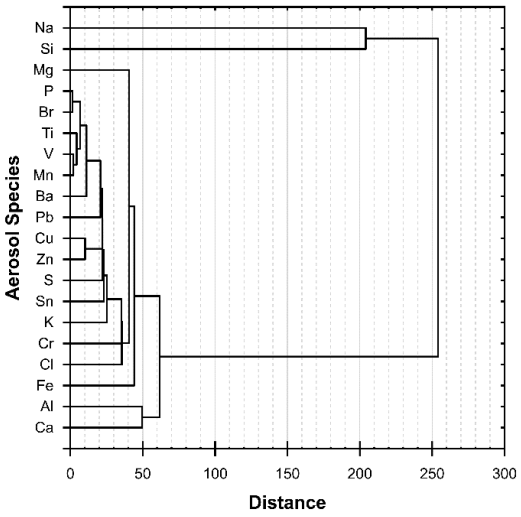


Figure D.27. The summer source characterisation results for the residential indoor environment of OSFB households, within the wood-burning settlement of Agincourt in South Africa (N=440) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

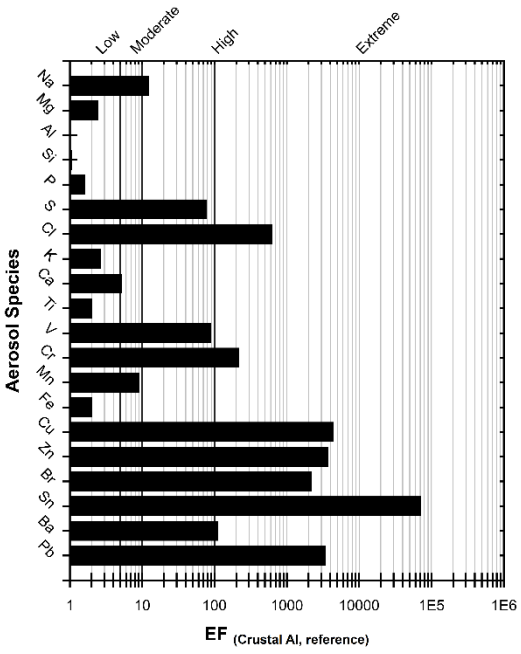
A **PCA (Varimax Rotated)**

Receptor	W-AG-W				
Source	Road Traffic	Crustal Soil	Road Traffic	Bio. Burn	Waste Burn
	F1	F2	F3	F4	F5
Na	0.05	0.33	0.01	**0.88**	0.03
Mg	-0.17	0.66	0.00	0.33	0.01
Al	0.23	**0.92**	0.04	0.11	-0.02
Si	0.08	**0.95**	0.02	0.16	0.01
P	0.04	**0.91**	0.00	0.12	-0.01
S	-0.03	**0.54**	0.00	-0.21	0.27
Cl	0.17	0.12	0.02	**0.95**	0.03
K	0.06	**0.90**	0.02	0.17	0.05
Ca	0.11	**0.82**	0.05	0.03	-0.05
Ti	**0.73**	**0.63**	0.08	0.10	-0.09
V	**0.98**	0.00	0.09	0.04	-0.10
Cr	0.13	-0.04	**0.98**	0.00	0.03
Mn	**0.93**	0.09	0.30	0.05	-0.08
Fe	0.13	0.13	**0.98**	0.03	0.03
Cu	**0.97**	0.07	-0.05	0.08	0.14
Zn	0.49	0.29	-0.15	0.13	**0.55**
Br	-0.05	0.00	0.11	0.00	0.34
Sn	-0.14	-0.04	-0.11	0.01	**0.78**
Ba	**0.98**	0.00	0.10	0.04	-0.11
Pb	**0.98**	0.00	0.00	0.04	-0.10
Expl.Var	5.65	5.42	2.09	1.95	1.16
Prp.Totl	0.28	0.27	0.10	0.10	0.06
Eigenvalue	7.09	4.51	1.98	1.58	1.13
Var. %	35.44	22.57	9.88	7.88	5.63
Cum. %	35.44	58.01	67.88	75.76	81.39

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

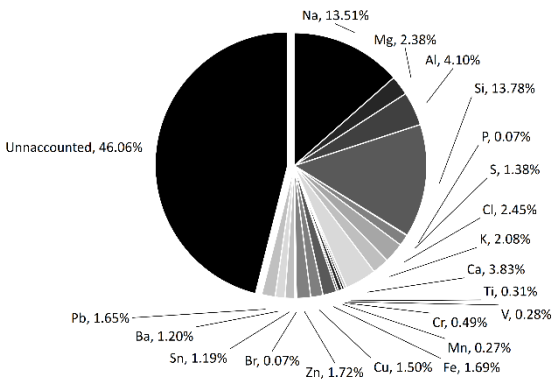
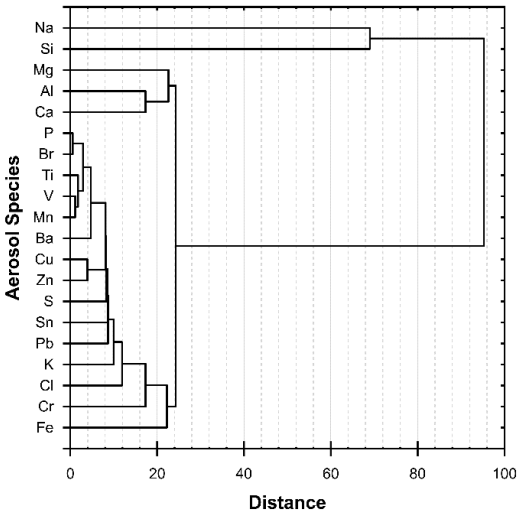


Figure D.28. The winter source characterisation results for the residential indoor environment within the wood-burning settlement of Agincourt, in South Africa (N=609) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

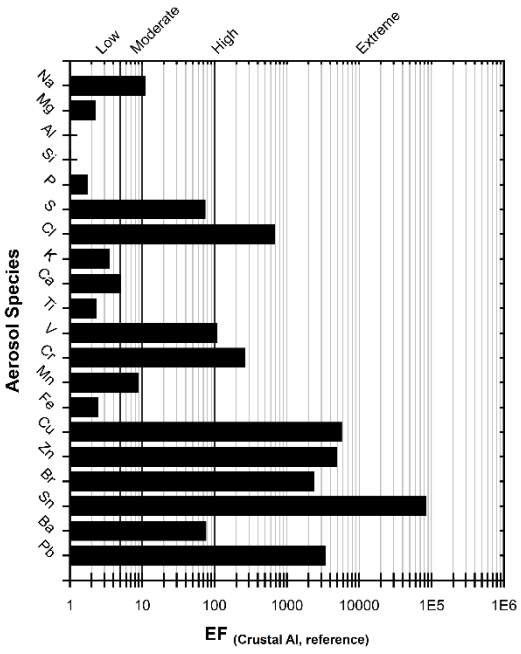
A **PCA (Varimax Rotated)**

Receptor	W-AG-W-ISFB				
Source	Crustal Soil	Road Traffic	Road Traffic	Bio. Burn	Waste Burn
	F1	F2	F3	F4	F5
Na	0.33	0.04	-0.04	**0.89**	-0.04
Mg	**0.75**	-0.19	-0.05	-0.10	0.06
Al	**0.88**	0.25	0.12	0.24	0.06
Si	**0.90**	0.13	0.05	0.28	0.03
P	**0.90**	0.02	0.02	0.28	-0.03
S	**0.76**	-0.16	0.03	-0.01	-0.14
Cl	0.10	0.13	0.05	**0.93**	-0.01
K	**0.80**	0.17	0.09	0.40	0.01
Ca	**0.88**	0.05	0.15	-0.05	0.10
Ti	**0.56**	**0.76**	0.13	0.18	0.08
V	-0.04	**0.98**	0.11	0.05	0.05
Cr	0.05	0.15	**0.98**	0.00	0.02
Mn	0.05	**0.89**	0.43	0.07	0.05
Fe	0.18	0.14	**0.97**	0.02	0.03
Cu	0.05	**0.96**	-0.05	0.03	-0.23
Zn	0.38	0.19	-0.17	0.05	**-0.72**
Br	0.17	-0.07	-0.02	0.00	0.25
Sn	-0.06	-0.31	0.03	0.00	**-0.76**
Ba	-0.05	**0.98**	0.12	0.05	0.06
Pb	-0.06	**0.99**	-0.04	0.05	0.04
Expl.Var	5.62	5.58	2.22	2.08	1.27
Prp.Totl	0.28	0.28	0.11	0.10	0.06
Eigenvalue	7.11	4.91	2.04	1.50	1.21
Var. %	35.55	24.54	10.19	7.49	6.06
Cum. %	35.55	60.09	70.28	77.77	83.83

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

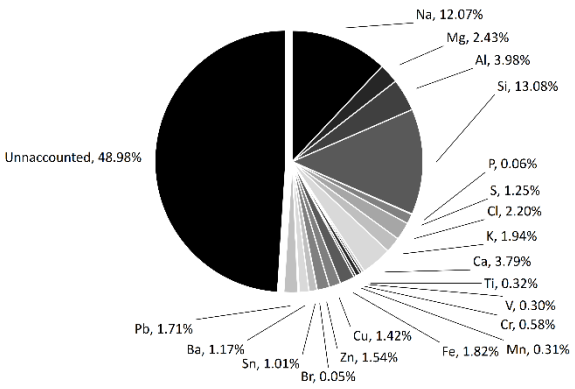
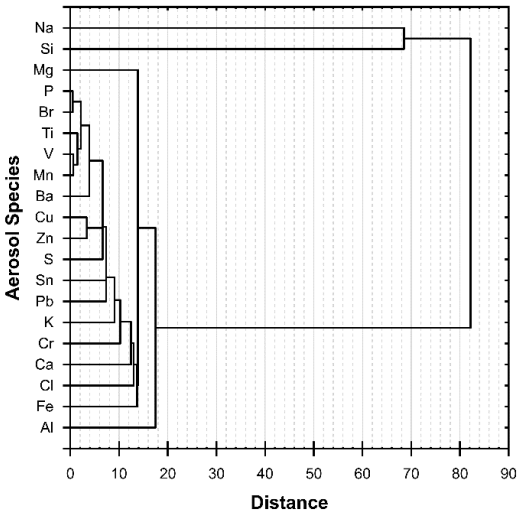


Figure D.29. The winter source characterisation results for the residential indoor environment of ISFB households, within the wood-burning settlement of Agincourt, in South Africa (N=94) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

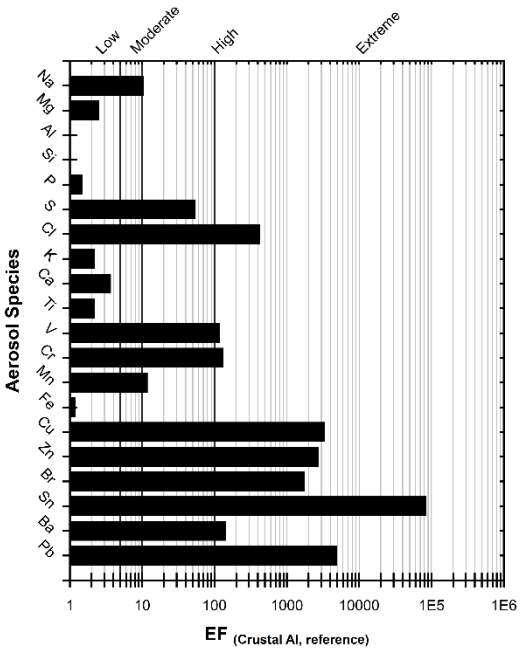
A **PCA (Varimax Rotated)**

Receptor	W-AG-W-NSFB				
Source	Road Traffic	Crustal Soil	Road Traffic	Bio. Burn	Waste Burn
	F1	F2	F3	F4	F5
Na	0.00	0.25	-0.13	**0.90**	-0.01
Mg	-0.36	0.26	0.01	**0.73**	0.02
Al	0.08	**0.91**	0.00	0.14	0.10
Si	-0.03	**0.94**	0.02	0.20	0.03
P	-0.11	**0.87**	0.03	0.19	-0.19
S	-0.28	**0.67**	0.02	-0.18	0.07
Cl	0.07	0.00	-0.07	**0.95**	-0.07
K	-0.12	**0.92**	0.04	0.02	-0.04
Ca	0.00	**0.69**	0.00	0.24	-0.20
Ti	**0.78**	**0.57**	-0.04	0.01	0.09
V	**0.98**	-0.12	-0.08	-0.09	0.03
Cr	0.14	-0.12	**-0.97**	-0.04	0.09
Mn	**0.94**	-0.08	-0.31	-0.05	0.06
Fe	**0.08**	0.06	**-0.98**	0.01	0.11
Cu	**0.94**	-0.13	0.08	-0.02	-0.20
Zn	0.16	0.12	0.32	0.06	**-0.76**
Br	-0.05	0.02	0.12	0.39	-0.03
Sn	-0.13	0.01	-0.04	0.03	**-0.86**
Ba	**0.98**	-0.12	-0.08	-0.08	0.05
Pb	**0.98**	-0.12	0.03	-0.08	0.04
Expl.Var	5.57	4.80	2.16	2.62	1.50
Prp.Totl	0.28	0.24	0.11	0.13	0.07
Eigenvalue	6.20	4.71	2.34	2.19	1.22
Var. %	30.98	23.56	11.71	10.93	6.08
Cum. %	30.98	54.54	66.25	77.18	83.26

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

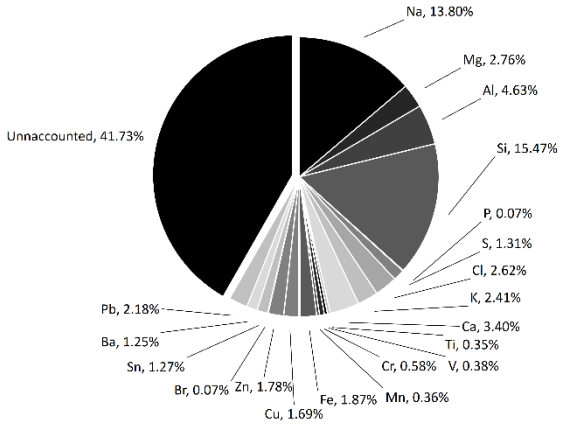
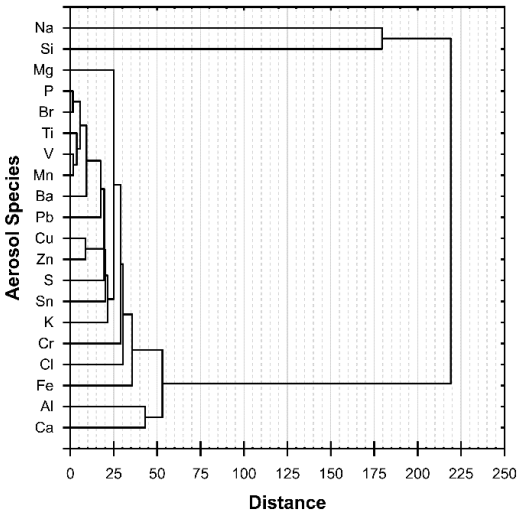


Figure D.30. The winter source characterisation results for the residential indoor environment of NSFB households, within the wood-burning settlement of Agincourt, in South Africa (N=60) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

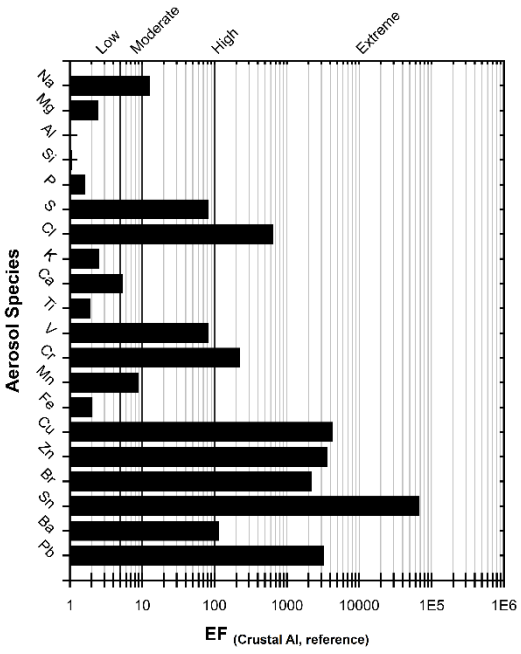
A **PCA (Varimax Rotated)**

Receptor	W-AG-W-OSFB				
Source	Crustal Soil	Road Traffic	Road Traffic	Bio. Burn	Waste Burn
	F1	F2	F3	F4	F5
Na	0.34	0.07	0.02	**0.87**	0.01
Mg	**0.74**	-0.12	0.00	0.36	0.01
Al	**0.93**	0.24	0.03	0.09	-0.01
Si	**0.95**	0.07	0.02	0.15	0.02
P	**0.91**	0.05	0.01	0.09	-0.04
S	0.46	0.05	-0.03	-0.23	0.38
Cl	0.14	0.20	0.01	**0.94**	-0.03
K	**0.91**	0.05	0.01	0.18	0.06
Ca	**0.83**	0.13	0.03	0.01	-0.07
Ti	**0.65**	**0.71**	0.07	0.09	-0.07
V	0.03	**0.98**	0.09	0.04	-0.09
Cr	-0.06	0.11	**0.98**	0.01	0.02
Mn	0.11	**0.94**	0.26	0.05	-0.08
Fe	0.12	0.13	**0.97**	0.03	0.03
Cu	0.10	**0.96**	-0.04	0.11	0.11
Zn	0.29	**0.56**	-0.12	0.18	**0.45**
Br	-0.04	-0.03	0.15	-0.05	0.46
Sn	-0.04	-0.13	-0.13	0.06	**0.73**
Ba	0.03	**0.98**	0.10	0.03	-0.11
Pb	0.03	**0.98**	0.02	0.04	-0.09
Expl.Var	5.57	5.71	2.06	1.96	1.15
Prp.Totl	0.28	0.29	0.10	0.10	0.06
Eigenvalue	7.43	4.36	1.95	1.58	1.12
Var. %	37.17	21.80	9.77	7.88	5.62
Cum. %	37.17	58.97	68.74	76.62	82.24

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

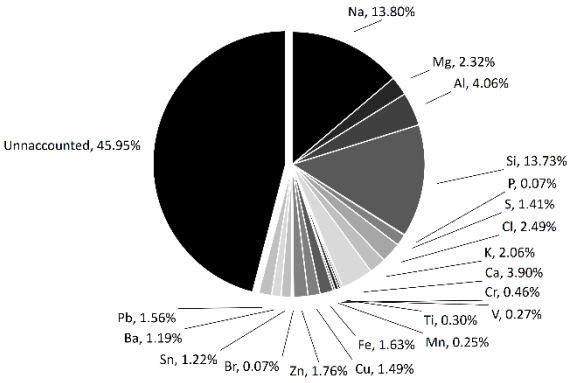
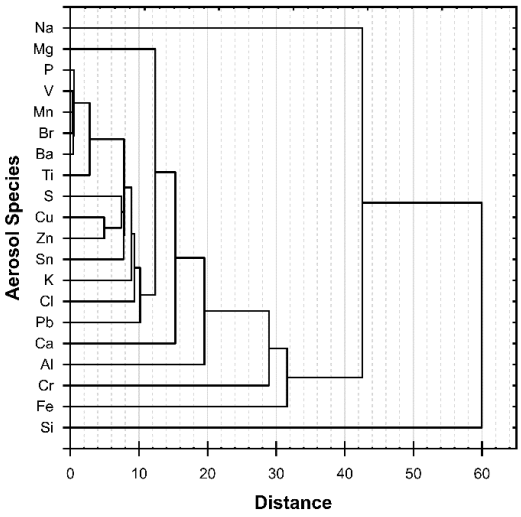


Figure D.31. The winter source characterisation results for the residential indoor environment of OSFB households, within the wood-burning settlement of Agincourt, in South Africa (N=455) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

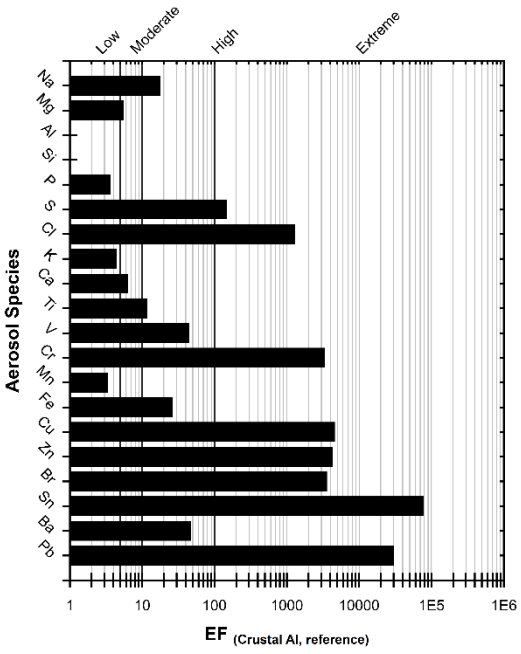
A **PCA (Varimax Rotated)**

Receptor	W-GY				
Source	Crustal Soil	Road Traffic	Road Traffic	Bio. Burn	Bio. Burn
	F1	F2	F3	F4	F5
Na	**0.64**	-0.01	0.06	**0.66**	-0.06
Mg	**0.74**	0.00	0.13	-0.07	0.07
Al	**0.90**	0.02	-0.03	0.04	-0.15
Si	**0.94**	0.02	-0.01	0.03	-0.12
P	**0.89**	0.00	0.03	0.04	0.00
S	**0.73**	0.00	0.06	0.23	0.08
Cl	0.12	0.14	0.03	**0.88**	0.00
K	**0.94**	0.06	0.05	0.06	0.05
Ca	**0.78**	0.08	0.03	0.11	-0.03
Ti	**0.84**	0.40	-0.07	0.04	-0.04
V	0.06	0.15	-0.33	-0.41	-0.27
Cr	-0.20	-0.19	**-0.94**	-0.06	0.08
Mn	**0.76**	0.11	0.16	-0.11	-0.04
Fe	0.00	-0.19	**-0.95**	-0.09	0.07
Cu	0.10	**0.98**	0.09	0.06	0.04
Zn	0.14	**0.96**	0.01	0.07	0.03
Br	0.08	-0.02	0.03	-0.03	**0.78**
Sn	-0.09	0.36	0.04	**0.50**	-0.33
Ba	-0.27	0.22	-0.25	0.00	**0.53**
Pb	0.09	**0.93**	0.31	0.06	0.02
Expl.Var	6.93	3.21	2.13	1.74	1.15
Prp.Totl	0.35	0.16	0.11	0.09	0.06
Eigenvalue	7.38	3.30	1.90	1.47	1.11
Var. %	36.89	16.51	9.48	7.36	5.53
Cum. %	36.89	53.40	62.88	70.24	75.78

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

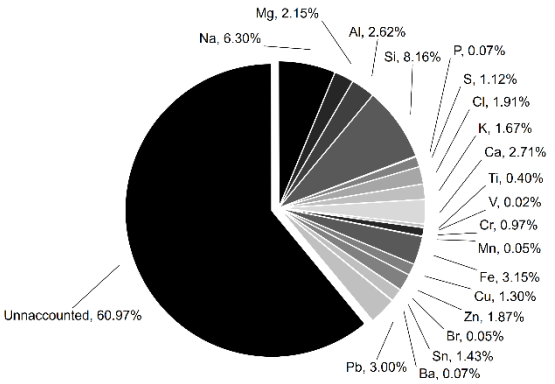
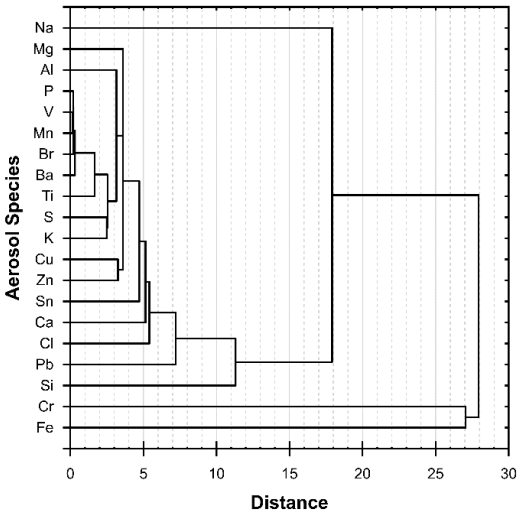


Figure D.32. The source characterisation results for the residential indoor environment within the wood-burning settlement of Giyani, in South Africa (N=110) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

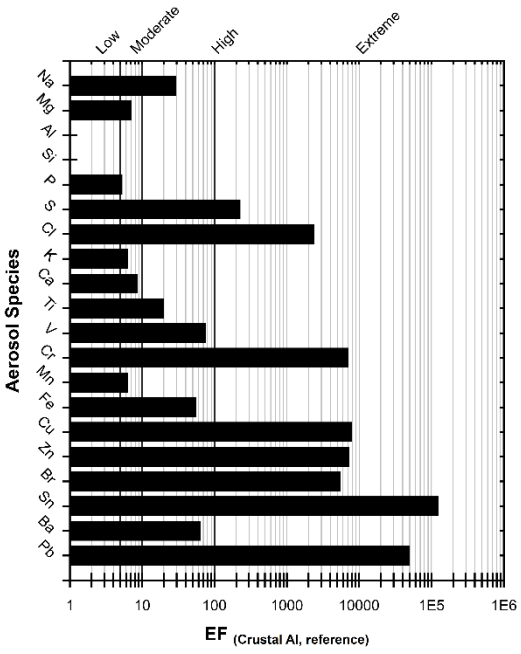
A **PCA (Varimax Rotated)**

Receptor	W-GY-S				
Source	Road Traffic	Crustal Soil	Road Traffic	Bio. Burn	Bio. Burn
	F1	F2	F3	F4	F5
Na	-0.01	0.24	0.11	**0.87**	-0.01
Mg	0.01	**0.53**	0.09	0.66	0.08
Al	0.34	**0.85**	0.07	0.02	0.24
Si	0.33	**0.85**	0.07	0.08	0.26
P	0.07	**0.82**	0.08	0.22	-0.07
S	0.00	**0.53**	0.27	0.13	-0.49
Cl	0.30	0.05	0.01	**0.88**	-0.05
K	0.48	**0.68**	0.07	0.32	0.01
Ca	0.29	**0.79**	0.05	0.16	0.03
Ti	**0.87**	0.44	-0.06	0.04	0.01
V	-0.08	-0.13	-0.52	0.20	0.25
Cr	-0.15	-0.07	**-0.91**	-0.18	-0.18
Mn	0.27	0.20	0.16	0.40	**0.55**
Fe	-0.14	-0.04	**-0.92**	-0.18	-0.17
Cu	**0.95**	0.20	0.12	0.09	-0.04
Zn	**0.94**	0.24	0.03	0.05	-0.03
Br	0.14	-0.15	-0.10	0.08	**-0.68**
Sn	0.45	0.08	0.29	0.19	0.02
Ba	0.39	-0.33	-0.27	-0.29	0.02
Pb	**0.87**	0.20	0.37	0.12	0.00
Expl.Var	4.44	4.36	2.42	2.57	1.28
Prp.Totl	0.22	0.22	0.12	0.13	0.06
Eigenvalue	7.64	2.58	2.09	1.55	1.21
Var. %	38.18	12.89	10.45	7.76	6.07
Cum. %	38.18	51.07	61.51	69.28	75.34

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

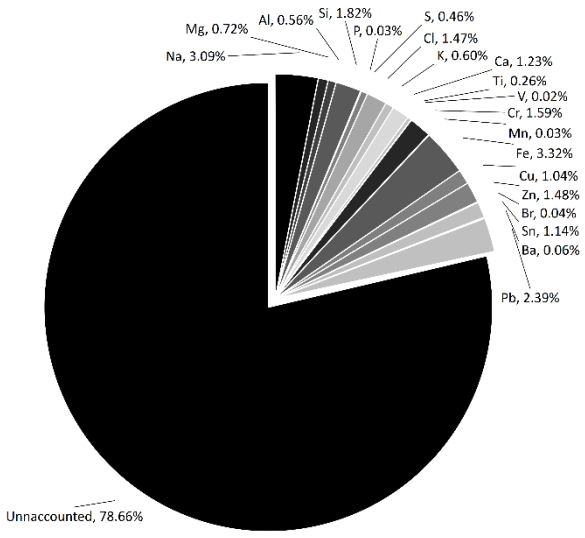
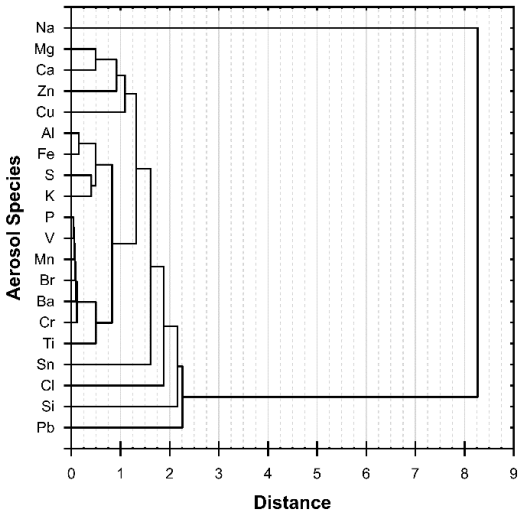


Figure D.33. The summer source characterisation results for the residential indoor environment within the wood-burning settlement of Giyani, in South Africa (N=52) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

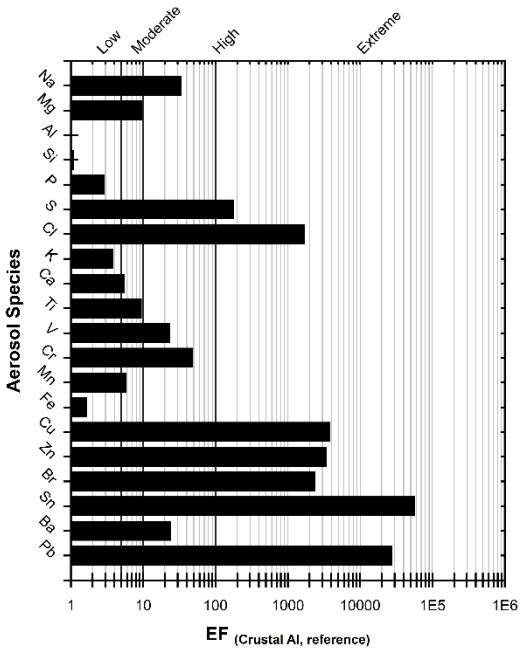
A **PCA (Varimax Rotated)**

Receptor	W-GY-S-NSFB				
Source	Road Traffic	Bio. Burn	Crustal Soil	Bio Burn.	Bio. Burn
	F1	F2	F3	F4	F5
Na	-0.15	0.46	-0.49	**-0.66**	-0.29
Mg	0.18	0.45	**0.86**	-0.12	-0.07
Al	0.11	-0.16	**0.95**	0.20	0.14
Si	0.14	-0.09	**0.98**	0.09	0.07
P	0.45	0.10	**0.79**	0.28	0.29
S	-0.31	-0.03	-0.18	0.05	**-0.86**
Cl	0.16	**0.54**	-0.37	**-0.73**	-0.06
K	**0.53**	-0.25	0.03	**-0.78**	0.10
Ca	0.41	0.18	**0.86**	-0.21	0.01
Ti	**0.90**	-0.01	0.31	0.02	0.24
V	0.05	**0.91**	0.34	-0.02	-0.02
Cr	**0.84**	-0.28	0.26	0.14	0.20
Mn	-0.17	-0.02	0.02	**-0.96**	0.21
Fe	0.23	0.12	**0.95**	0.15	0.08
Cu	**0.98**	0.09	0.18	-0.01	0.10
Zn	**0.94**	0.17	0.29	0.00	0.06
Br	**0.69**	0.02	0.19	0.30	-0.39
Sn	-0.15	0.09	-0.03	**-0.94**	-0.26
Ba	0.16	-0.47	0.15	0.51	**0.68**
Pb	**0.98**	0.04	0.06	-0.10	0.18
Expl.Var	5.76	2.03	5.74	3.99	1.83
Prp.Totl	0.29	0.10	0.29	0.20	0.09
Eigenvalue	8.85	4.47	3.14	1.83	1.05
Var. %	44.27	22.36	15.70	9.16	5.24
Cum. %	44.27	66.62	82.32	91.49	96.73

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

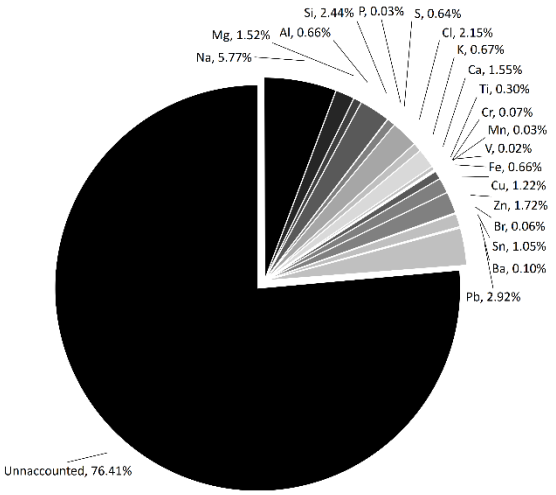
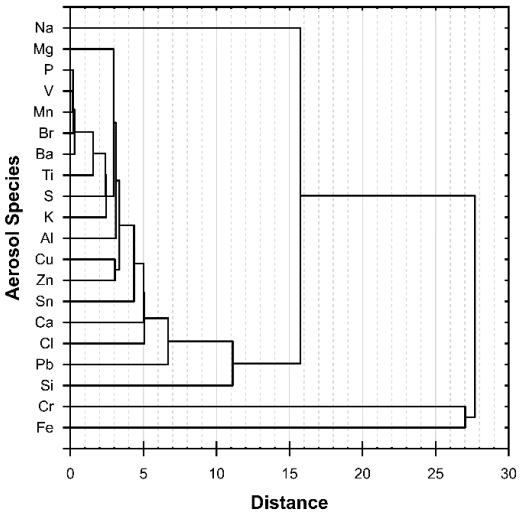


Figure D.34. The summer source characterisation results for the residential indoor environment of NSFB households, within the wood-burning settlement of Giyani, in South Africa (N=7) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

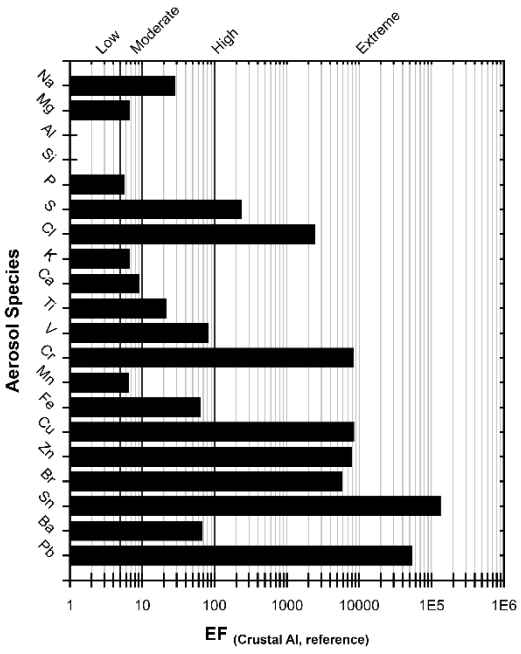
A **PCA (Varimax Rotated)**

Receptor	W-GY-S-OSFB				
Source	Road Traffic	Crustal Soil	Road Traffic	Bio Burn.	Bio Burn.
	F1	F2	F3	F4	F5
Na	0.01	0.31	0.11	**0.84**	-0.03
Mg	0.01	**0.57**	0.09	**0.67**	0.15
Al	0.39	**0.81**	0.05	0.04	0.29
Si	0.37	**0.81**	0.06	0.09	0.31
P	0.08	**0.82**	0.10	0.30	-0.05
S	0.08	**0.57**	0.23	0.05	**-0.52**
Cl	0.30	0.06	0.04	**0.87**	-0.08
K	**0.51**	**0.66**	0.07	0.34	0.02
Ca	0.32	**0.77**	0.04	0.16	0.08
Ti	**0.89**	0.39	-0.06	0.08	0.05
V	-0.13	-0.15	-0.48	0.18	0.28
Cr	-0.15	-0.07	**-0.92**	-0.16	-0.20
Mn	0.30	0.21	0.17	0.36	**0.57**
Fe	-0.14	-0.04	**-0.93**	-0.15	-0.19
Cu	**0.95**	0.17	0.14	0.12	0.01
Zn	**0.95**	0.20	0.04	0.07	0.02
Br	0.08	-0.20	-0.13	0.15	**-0.55**
Sn	**0.50**	0.10	0.34	0.12	-0.17
Ba	0.39	-0.44	-0.32	-0.11	0.07
Pb	**0.87**	0.17	0.38	0.13	0.04
Expl.Var	4.68	4.34	2.48	2.46	1.31
Prp.Totl	0.23	0.22	0.12	0.12	0.07
Eigenvalue	7.90	2.54	2.08	1.52	1.22
Var. %	39.50	12.71	10.39	7.58	6.12
Cum. %	39.50	52.21	62.60	70.19	76.31

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

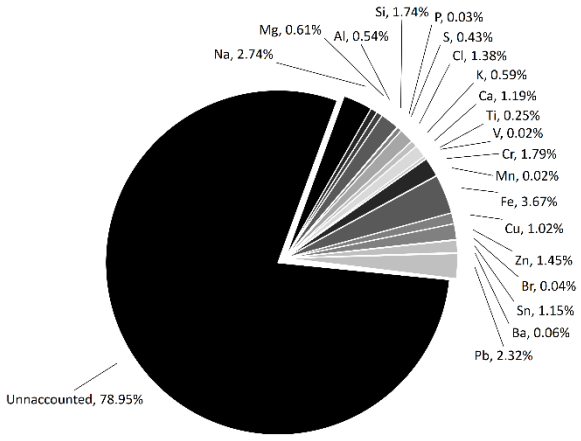
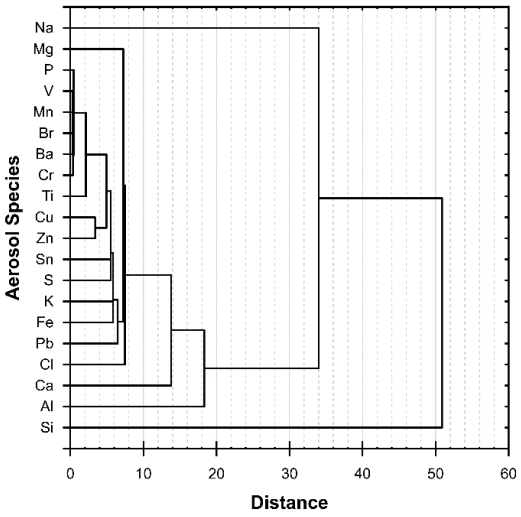


Figure D.35. The summer source characterisation results for the residential indoor environment of OSFB households, within the wood-burning settlement of Giyani, in South Africa (N=45) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

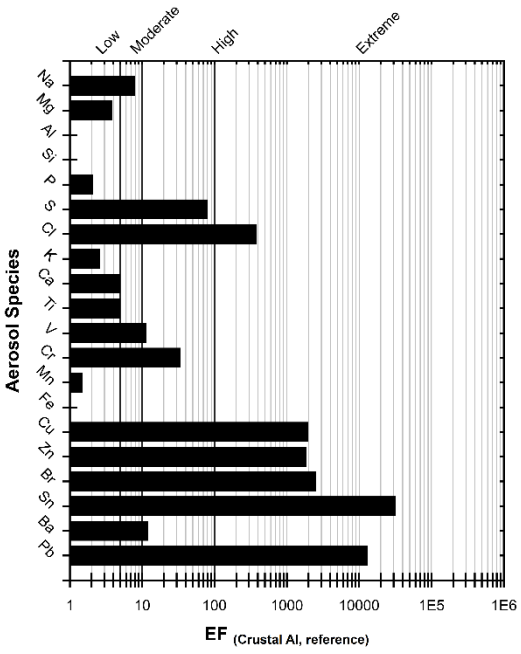
A **PCA (Varimax Rotated)**

Receptor	W-GY-W				
Source	Crustal Soil	Road Traffic	Bio. Burn	Bio. Burn	Bio. Burn
	F1	F2	F3	F4	F5
Na	0.49	-0.04	**0.79**	-0.05	0.11
Mg	0.26	-0.16	0.19	**0.61**	0.33
Al	**0.93**	-0.10	0.07	0.10	0.20
Si	**0.92**	-0.11	0.08	0.12	0.26
P	0.45	-0.06	0.12	0.04	**0.85**
S	**0.55**	-0.02	0.27	-0.43	0.25
Cl	-0.02	0.02	**0.93**	0.06	0.02
K	**0.68**	-0.03	0.18	-0.13	0.62
Ca	0.31	-0.02	0.05	0.02	**0.88**
Ti	**0.90**	0.15	0.06	-0.05	0.21
V	0.27	**0.53**	-0.43	-0.31	-0.03
Cr	0.00	0.09	-0.20	0.36	0.07
Mn	**0.61**	0.10	-0.06	0.27	0.14
Fe	**0.91**	-0.13	-0.02	0.27	0.09
Cu	-0.07	**0.97**	0.07	0.06	-0.02
Zn	-0.07	**0.95**	0.09	0.10	0.10
Br	-0.17	-0.05	-0.09	**-0.73**	0.16
Sn	-0.03	0.20	**0.56**	-0.08	0.14
Ba	-0.32	0.13	0.11	0.12	0.27
Pb	-0.06	**0.96**	0.08	0.00	-0.11
Expl.Var	5.31	3.21	2.25	1.56	2.39
Prp.Totl	0.27	0.16	0.11	0.08	0.12
Eigenvalue	6.61	3.19	2.09	1.55	1.28
Var. %	33.03	15.95	10.44	7.76	6.38
Cum. %	33.03	48.97	59.42	67.18	73.55

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

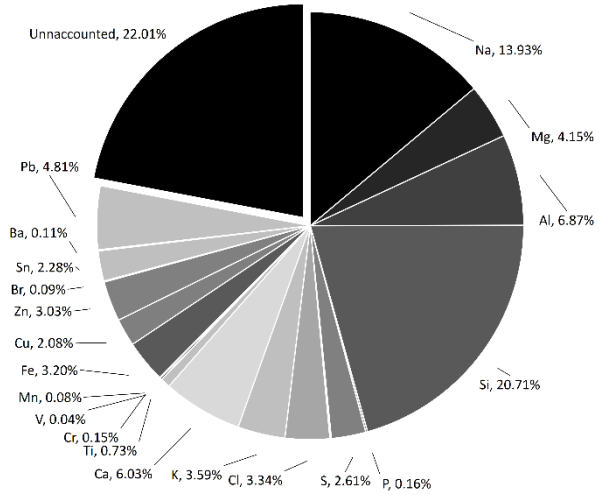
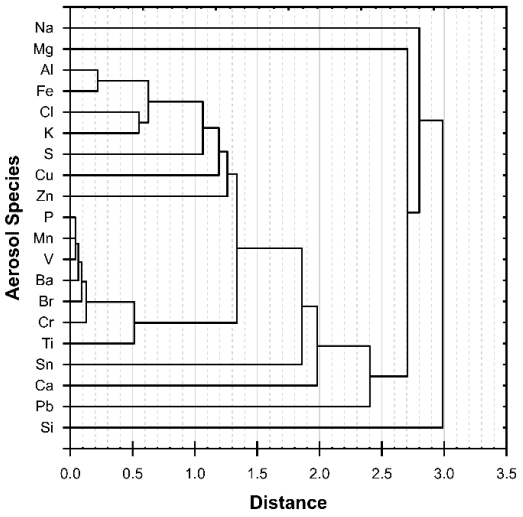


Figure D.36. The winter source characterisation results for the residential indoor environment within the wood-burning settlement of Giyani, in South Africa (N=49) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

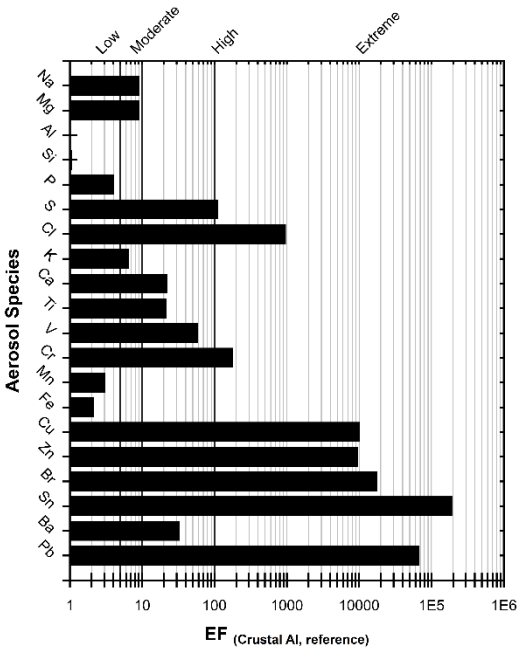
A **PCA Varimax Rotated**

Receptor	W-GY-W-NSFB				
Source	Crustal Soil	Road Traffic	Bio. Burn	Bio. Burn	Bio. Burn
	F1	F2	F3	F4	F5
Na	0.43	0.09	**0.81**	-0.17	0.09
Mg	0.22	-0.14	0.23	**0.53**	0.43
Al	**0.94**	-0.08	0.06	0.06	0.24
Si	**0.92**	-0.08	0.06	0.08	0.31
P	0.36	0.01	0.04	-0.02	**0.89**
S	0.43	-0.14	0.22	**-0.62**	0.23
Cl	-0.10	0.21	**0.89**	-0.01	0.00
K	**0.61**	0.01	0.09	-0.25	**0.68**
Ca	0.27	0.06	0.00	-0.03	**0.89**
Ti	**0.89**	0.12	0.01	-0.11	0.23
V	0.23	**0.36**	-0.59	-0.33	-0.08
Cr	0.05	0.17	-0.20	0.29	0.03
Mn	**0.53**	-0.02	-0.14	0.32	0.17
Fe	**0.92**	-0.15	-0.01	0.22	0.13
Cu	-0.04	**0.96**	0.01	0.06	-0.03
Zn	-0.01	**0.95**	0.06	0.09	0.13
Br	-0.20	-0.02	-0.13	**-0.69**	0.12
Sn	-0.06	0.49	0.42	0.00	0.13
Ba	-0.34	-0.06	0.21	0.08	0.28
Pb	-0.06	**0.93**	-0.02	0.00	-0.15
Expl.Var	4.86	3.24	2.22	1.62	2.71
Prp.Totl	0.24	0.16	0.11	0.08	0.14
Eigenvalue	6.13	3.27	2.19	1.65	1.39
Var. %	30.66	16.37	10.97	8.26	6.97
Cum. %	30.66	47.03	58.00	66.26	73.22

B **Hierarchical cluster analysis**



C **Enrichment Factors (Crustal Al as reference)**



D **Elemental Abundance %**

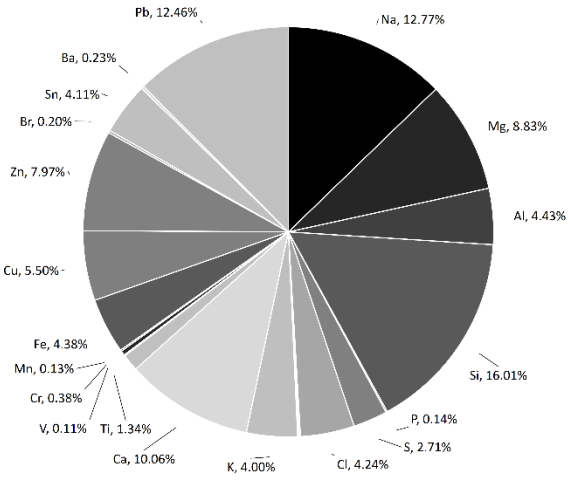
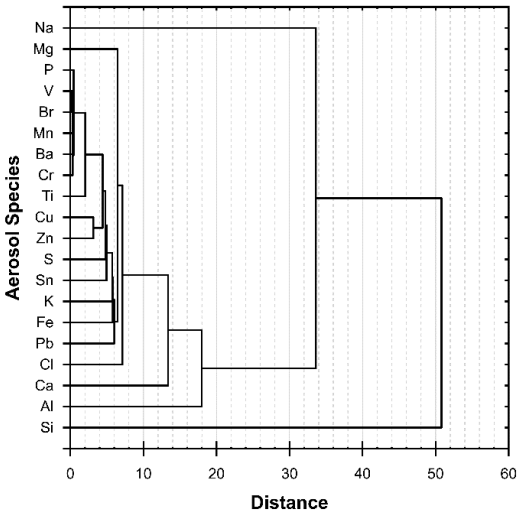


Figure D.37. The winter source characterisation results for the residential indoor environment of NSFB households, within the wood-burning settlement of Giyani, in South Africa (N=6) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.

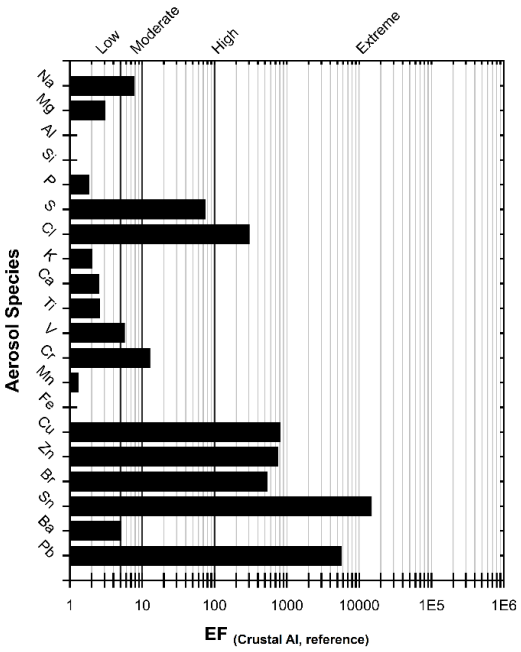
A **PCA (Varimax Rotated)**

Receptor	W-GY-W-OSFB			
Source	Crustal Soil	Road Traffic	Bio. Burn	Road Traffic
	F1	F2	F3	F4
Na	**0.92**	0.34	-0.16	0.04
Mg	**0.99**	-0.06	0.00	0.09
Al	**0.99**	0.05	0.06	0.11
Si	**0.99**	0.01	0.05	0.11
P	**0.98**	0.06	0.08	0.14
S	0.48	**0.87**	0.05	0.02
Cl	**0.96**	-0.03	-0.26	-0.08
K	**0.92**	0.35	0.17	0.00
Ca	0.20	-0.20	**-0.87**	-0.40
Ti	0.42	**0.88**	0.07	-0.18
V	0.06	**0.98**	-0.17	0.04
Cr	0.29	-0.39	0.02	**0.86**
Mn	**0.56**	**0.69**	0.02	-0.32
Fe	1.00	0.04	0.02	0.05
Cu	-0.05	**0.96**	0.20	-0.14
Zn	-0.10	**0.94**	0.25	-0.17
Br	**-0.85**	-0.26	0.06	0.40
Sn	-0.14	-0.17	**-0.94**	0.26
Ba	0.06	**0.75**	0.44	0.32
Pb	-0.01	**0.98**	0.08	-0.20
Expl.Var	9.13	6.84	2.12	1.52
Prp.Totl	0.46	0.34	0.11	0.08
Eigenvalue	10.28	6.13	2.10	1.10
Var. %	51.39	30.65	10.50	5.52
Cum. %	51.39	82.04	92.53	98.06

B **Hierarchical cluster analysis**



C **Enrichment Factors (Ref: Crustal Al)**



D **Elemental Abundance (%)**

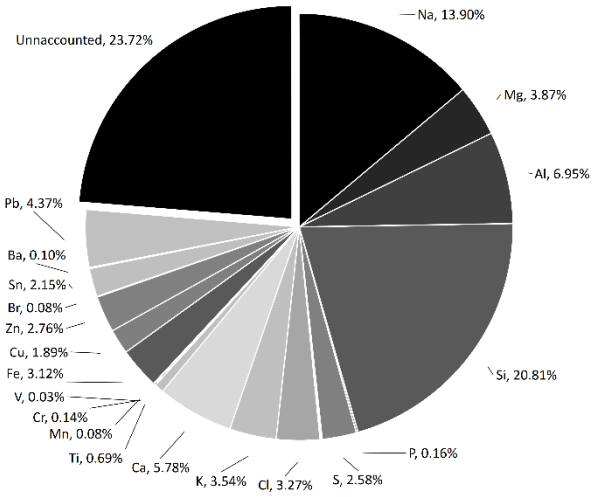


Figure D.38. The winter source characterisation results for the residential indoor environment of OSFB households, within the wood-burning settlement of Giyani, in South Africa (N=43) including the a) PCA Varimax rotated anlayis, b) cluster analysis, c) enrichment factors, and d) percentage element abundance.